Real losses from drinking water networks operated by gated communities

By

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Abstract

The International Water Association (IWA) has provided a standardised approach to better understand and manage water leakage and losses. Prior studies have focused predominately on quantifying the extent of water loss within municipal water networks, while neglecting relatively smaller systems operated by gated communities (GCs). Normal distribution systems are held responsible by municipal authorities as opposed to smaller, well maintained and self-managed infrastructures in GCs. The provision of added security and lifestyle improvements has seen a gradual rise in the number of GCs as more people feel the urge to relocate from freestanding properties.

As part of this research, real losses in the distribution systems of three selected GCs were analysed with a focus on the minimum night flow (MNF). The first challenge was to gain access to an existing remote sensing platform, because it was beyond the scope of this research to install meters and/or a metering system. After identifying relevant collaborators, the databases had to be scrutinised in order to identify and isolate flow rates of selected GCs, with data at a sufficient resolution and a sufficiently long time series to enable analysis of night flows. Bulk meter flow rates for three suitable GCs were extracted over a 12 month time frame from a total database in excess of 35040 daily readings, linked to an existing remote sensing system. The collected data had regular intervals of 15 minutes recorded between 1 October 2018 and 30 September 2019. The ultimate data set, used for the analyses, comprised 34 944 flow rate recordings for each of the three GCs. The implementation of a stringent categorisation, selection and verification process resulted in the consolidation of a feasible data record catalogue.

Research found that GC A had a current annual real loss (CARL) of 8.30 kL/d, or 21 % of the average daily consumption. The unavoidable annual real loss (UARL) component varied between 4.32 and 7.19 kL/d for the assumed average operating pressure. GC B reported a comparable CARL of 7.89 kL/d, representative of a 15 % loss. A UARL range between 4.83 and 8.06 kL/d was recorded for GC B. Lastly; GC C held a relatively higher CARL of 52 % in accordance with a 14.36 kL/d real loss. Values representative of the UARL in GC C were 6.36 to 10.60 kL/d.

Research concluded that all GCs had a relatively low loss in relation to the UARL, with infrastructure leakage values. The infrastructure leakage index values for all three sites were

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exceptionally low for typical South African conditions. This is possibly due to better water distribution system operation and management in GCs than evident elsewhere. The research highlights several discrepancies, suggesting potential adjustments to water loss approximations for GCs, while establishing recommendations for future research.

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Opsomming

Die International Water Association (IWA) het 'n gestandaardiseerde benadering om waterlekkasie en -verlies beter te verstaan en bestuur. Vorige studies het hoofsaaklik op die kwantifisering van die omvang van waterverlies binne munisipale waternetwerke gefokus, terwyl relatief kleiner stelsels wat deur omheinde gemeenskappe (OGe) bedryf word geignoreer was. Normale verspreidingstelsels word deur munisipale owerhede verantwoordelik gehou in plaas van kleiner, goed onderhoude en selfbestuurde infrastrukture in OGe. Die ekstra veiligheid en verbetering wan lewenstyl wat OGe aanbied het gelei tot die geleidelike toename in die aantal OGe was bestaan omdat meer mense die drang voel om van losstaande eiendomme te verhuis.

As deel van hierdie studie is reële verliese in die verspreidingstelsels van drie geselekteerde OGe geanaliseer met ‘n fokus op die minimum nagvloei (MNV). Die eerste uitdaging was om toegang tot 'n bestaande afstandswaarnemingsplatform te kry, omdat dit buite die bestek van hierdie studie was om meters en / of 'n meetstelsel te installeer. Na die identifisering van relevante medewerkers, moes die databasisse ondersoek word om vloeitempo's van geselekteerde OGe te identifiseer en te isoleer - met data wat 'n voldoende resolusie en 'n lang genoeg tydreeks het om ontleding van nagvloei moontlik te maak. Die grootmaatmeters se vloeitempo's vir drie geskikte OGe is gedurende 'n keuringsperiode van 12 maande onttrek uit 'n totale databasis van meer as 840 960 lesings wat gekoppel is aan 'n bestaande afstandswaarnemingstelsel. Die versamelde data het tussen 1 Oktober 2018 en 30 September 2019 gereeld tussenposes van 15 minute aangeteken. Die datastel wat vir die ontledings op die einde gebruik was het bestaan van 34 944 vloeitempo-opnames vir elk van die drie OGe. Die implementering van 'n streng kategoriserings-, seleksie- en verifikasieproses het gelei tot die konsolidasie van 'n uitvoerbare datarekordkatalogus.

Die studie het bevind dat OG A 'n huidige jaarlikse reële verlies (HJRV) van 8.30 kL / d het, of 21% van die gemiddelde daaglikse verbruik. Die onvermydelike jaarlikse reële verlies (OJRV) gedeelte het vir die veronderstelde gemiddelde bedryfsdruk tussen 4,32 kL/d en 7,19 kL / d gewissel. GC B het 'n vergelykbare HJRV van ongeveer 7,89 kL / d gerapporteer, verteenwoordigend van 'n verlies van 15%. 'n UARL-reeks tussen 4,83 en 8,06 kL / d is aangeteken vir GC B. Laastens het GC C 'n relatief hoër HJRV van 52% gehou volgens 'n koers van 14,36 kL / d. Waardes wat die UARL verteenwoordig, is gemeet op 6,36 tot 10,60kL / d.

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List of Acronyms

AADD	Annual Average Daily Demand
AL	Apparent Losses
AOP	Average Operating Pressure
API	Application Programming Interface
AWWA	American Water Works Association
BABE	Bursts and Background Estimates
CARL	Current Annual Real Losses
CMA	Consumption Monitor Area
CSIR	Council for Scientific and Industrial Research
DEADP	Department of Environmental Affairs and Development Planning
DMA	District Metered Area
DWAF	Department of Water Affairs
DWS	Department of Water and Sanitation
FAVAD	Fixed Area and Variable Area Discharges
GC	Gated Community
GCM	Global System for Mobile Communications
ILI	Infrastructure Leakage Index
IWA	International Water Association
LDNC	Legitimate Domestic Night Consumption
LNC	Legitimate Night Consumption
LNHHNC	Legitimate Non-Household Night Consumption
MNF	Minimum Night Flow
NPR	National Performance Review
NRW	Non-Revenue Water
OFWAT	The Water Services Regulation Authority

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PK	Peak Factor
RL	Real Losses
SIV	System Input Volume
UAC	Unbilled Authorised Consumption
UARL	Unavoidable Annual Real Losses
WDM	Water Demand Management
WC	Water Conservation
WISA	Water Institute of Southern Africa
WRC	Water Research Commission
WL	Water Losses

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Standard Abbreviations for Units

Abbreviation	**Unit**
Length	
m	Metre
km	Kilometre
Flow	
m^3/h	Cubic metre per hour
m^3/yr	Cubic metre per year
L/s	Litre per second
L/h	Litre per hour
L/d	Litre per day
L/plot/h	Litre per plot per hour
m^3/km/d	Cubic metre per kilometre per day
L/km/d/m	Litre per kilometre per day per metre (of pressure)
L/con/d	Litre per connection per day
L/con/d/m	Litre per connection per day per metre (of pressure)
L/consumer/h	Litre per consumer per hour
Area	
m^2	Metre squared
ha	Hectare
Volume	
ML	Mega-Litre

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Pressure

Bar	Bar
m	Metre

Other

Con	Connection
%	Percentage

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Glossary

In order to ensure complete clarity, brief descriptions pertaining to certain concepts commonly used throughout this research are provided, as some technical terms may be construed as ambiguous or encompass several varying connotations.

AADD	Also known as Annual Average Daily Demand, is defined as the total volume of water used by a customer/customer group for the entirety of one year, divided by the number of days in the specified year (Arunkumar and Mariappan, 2015).
Day Zero	When the four million residents of Cape Town are required to collect daily water rations: less than seven gallons (25 litres) for each person.
District Metered Area	A section of the supply system where sluice valves have been shut off so that the water consumption in the area can be monitored for the purpose of leakage management (Pearson, 2019).
End use	The smallest identifiable use of water on a stand, such as a toilet flush (Jacobs and Haarhoff, 2004).
Minimum Night Flow	The MNF is defined as the minimum 1 hour flow rate recorded during the night time period between midnight and 6 am. However, in urban situations, MNF typically occurs between 2 and 4 am (Pearson, 2019).
Water conservation	The minimisation of loss of waste, the care and protection of water resources and the efficient and effective use of water (Department of Water Affairs, 2004).

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Water consumption The actual volume of water utilised by a consumer/consumer group, as measured by water meters placed on or near the property boundary (CSIR, 2005).

Water demand management "The adaptation and implementation of a strategy by a water institution or user to influence the water demand and usage of water in order to meet any of the following objectives: economic efficiency, social development, social equity, environmental protection, sustainability of water supply and services, and political acceptability" (Department of Human Settlement, 2019).

Water leakage and loss Various terms relating to the IWA water balance, water leakage and losses are used in the this thesis. All related definitions were adopted by Pearson (2019).

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1. Introduction

The objective of the chapter is to introduce the research undertaken through a brief description of the background in the components of water loss and leakage within gated communities. The term gated community (GC) was adopted from Du Plessis and Jacobs (2018) and will herewith be used throughout the research. Furthermore, defined within the chapter are the specified objectives, scope and constraints pertinent to the completion of the research.

1.1 Background

In many parts of the world, drinking water is supplied to consumers via pressurised water distribution systems (Lambert, 2002). Due to the relatively high internal pipe pressure, distribution systems experience higher pipe failure rates, reduced pipe service life and an increase of wasteful consumption as water tends to leak out of the system (Cassa *et al.*, 2010; Lambert *et al.*, 2013).

Potable water is a precious resource. The South African climate is predicted to become hotter and drier as early as 2030, particularly the Western Cape (Easterling *et al.*, 2000; Mason, 2001; Donat *et al.*, 2013 and Jury, 1995). Increasing temperatures, accompanied by unpredictable rainfall patterns, high evaporation rates and extreme weather conditions (DWAF, 2004; Department of Water Affairs, 2013) will place tremendous pressure on the importance of protecting and sustaining the available water resources. Furthermore, the “Day Zero” crisis in the Western Cape in 2017 (Burls *et al.*, 2019: Sousa *et al.*, 2018 and Booysen *et al.*, 2019) raised water scarcity awareness as the focus shifted from resource development to conserving water.

A number of studies investigated alternative water resource development solutions such as desalination plants, dual reticulation, water reuse and water efficient appliances (Gurung *et al.*, 2015). In light of the current and future threats to global water security (Fielding *et al.*, 2012), research focuses on testing interventions to promote urban water conservation such as improved efficiency, pressure reduction (Schwaller *et al.*, 2015) and leak repair (Pearson, 2019). Throughout the studies, few to date have focussed specifically on the extent of water loss within the water distribution systems of GCs.

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Water loss and leakage is a major problem globally and is well researched. DeOreo *et al.*, (1996) found that 20 % of households in Boulder, Colorado experienced leakage. Mayer *et al.*, (1999) discovered that across the USA, a small number of houses were responsible for the majority of the recorded leakage where 67 % of the houses held measureable leaks of 1.6 L/h whilst 5.5% of houses lost an average of 15.8 L/h. A study conducted in Spain found leakage rates ranging between 2 and 40 L/h with certain leaks reaching a high of 100 L/h (Arrequi *et al.*, 2006). Similarly, Gascón *et al.,* (2004) measured an average residential leakage rate of 17 L/h per household, representing 8.9% of the average daily consumption throughout various Spanish cities.

Investigations concerning leakage patterns on residential households concluded that 20% and 9% of houses experienced leakage in Windhoek and Swakopmund respectively, with leakage rates of 20.3 L/h and 9 L/h (Fourie, 2004). In Queensland, Australia, a study using smart metering found a leakage rate of only 3.5 % due to the consequence of homeowners being informed of trickle alerts on a regular basis. The average leakage rate was however found to be 30.8 L/h (Britton *et al.*, 2009). Finally, McKenzie (2002) found that system leakage was responsible for approximately 20 to 35 % of water loss through Cape Town's water distribution system.

It is apparent that residential water loss and leakage rates vary considerably. Research by Lightstone reported that there were approximately 6500 GCs in South Africa in 2016 (Paul-Roux de Kock, 2016). Numbers have since grown notably due to added security and lifestyle improvements offered by GCs (Landman, 2004). The International Water Association (IWA) has done extensive research to better understand and manage water leakage. Most focus predominately on municipal water distribution systems while neglecting the component of water losses that occur on consumer properties (Lugoma *et al.*, 2011). According to Farley and Trow (2003), on-site leakage is classified as revenue water and not water losses. Since municipalities are not responsible for water losses within GCs, there is a limited financial incentive for a municipality to address the problem and may even benefit through increased water sales. A GC is responsible for managing the infrastructure within the GC (Lugoma *et al.*, 2011). As a result of the aforementioned, further research addressing water losses within GCs would prove to be beneficial.

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1.2 Problem Statement

The extent of real losses in potable water distribution systems operated gated communities is unknown.

1.3 Goal

Investigate the extent of real losses in the water distribution systems of three selected gated communities, by investigating the minimum night flows.

1.4 Research Objectives

The research aims to quantify the extent of real losses within three selected water distribution systems. As a result, a better insight is gained with regards to the adversities associated with the water demand management strategies currently implemented for which mitigation measures can be recommended. To achieve the objective, significant data collection, modelling and analyses are deemed necessary whilst engaging with individuals with the requisite domain knowledge. In so doing, the following sub-objectives have been defined:

- Conduct a literature review of previous publications, both domestic and international, on residential water loss, consumption and leakage;
- Develop a model to approximate the residential minimum night flow (MNF) used in quantifying the extent of water loss;
- Collect relevant data sets to populate the aforementioned model parameters;
- Implement a data categorisation, selection and verification process to ensure that an accurate and feasible range of water flows are attained;
- Analyse the MNF sourced from the model as to estimate the volume of water loss within the system;
- Evaluate the findings and establish necessary conclusions.

1.5 Research Scope and Constraints

1.5.1 Scope

The focus of the research is on real losses, but the analysis of other components in the IWA water balance – including the total water consumption – was necessary in order to verify the data and segregate the real losses. As part of the research, a case study was included where data was collected from the field.

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The case study component was limited to the Western Cape and, more specifically, to three primary locations in which data flow records pertaining to GCs could be obtained. The research centres exclusively on residential water consumption within GCs for the reason that the aforementioned land zones fall within a higher income bracket with greater accuracy in bulk meter readings, efficient detection of leaks in addition to quicker repair response times (Du Plessis and Jacobs, 2018; Knox, 2020). The literature review, however, includes a brief review of the other components in the urban consumption profile. Furthermore, the research negates the necessity of predicting or expanding data records as this falls beyond the scope of the research and could potentially jeopardise the accuracy of the results.

The names of the GCs will not be disclosed but denoted as A, B and C. The locations and relative positions are indicated in Figure 1-1.

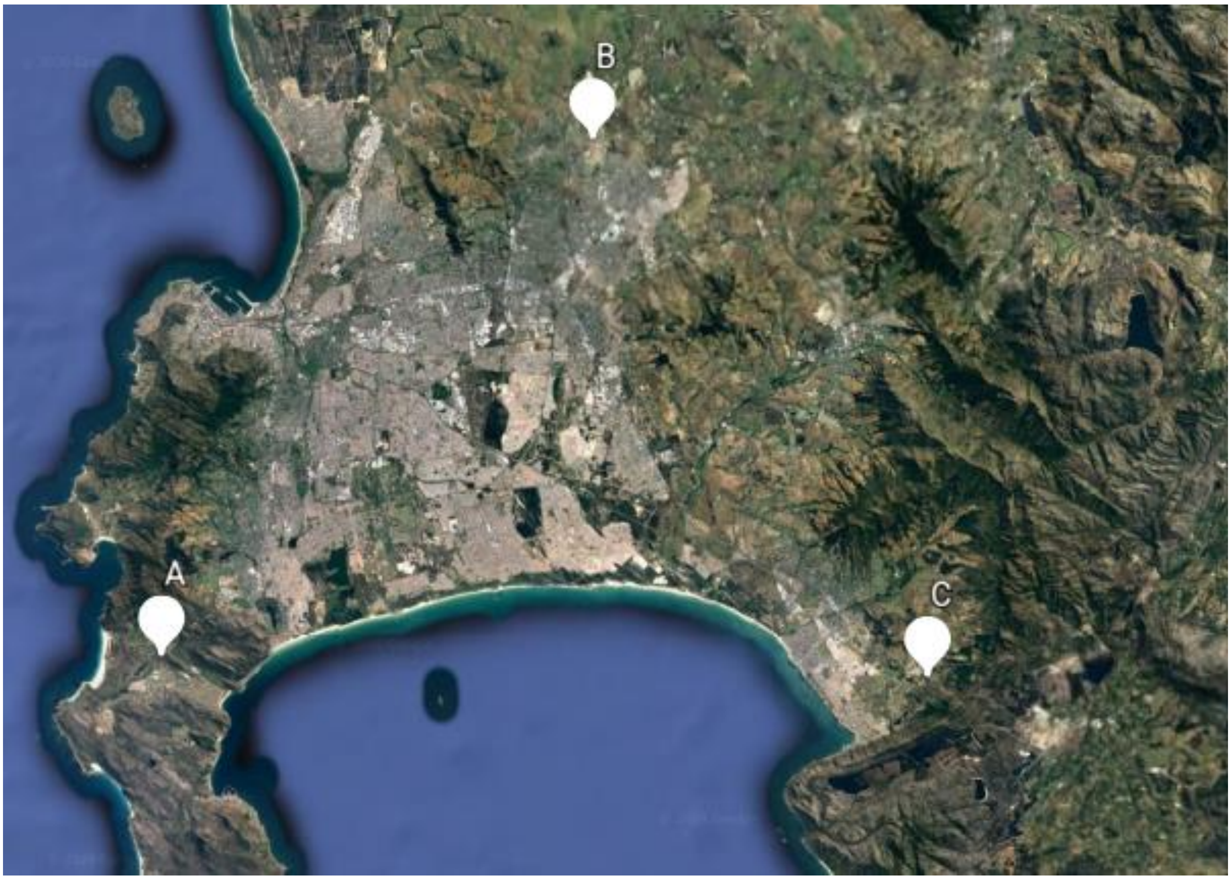

Figure 1-1: Relative positions of the selected GCs.

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1.5.2 Constraints

The data time series length was approximately one year, selected to best meet the desired criteria discussed in further detail in Chapter 4. Flow rates were collected at regular intervals of 15 minutes between 1 October 2018 and 30 September 2019. Although the numbers of households located within the GCs were known, data records were comprised entirely from bulk meters as individual house readings were unobtainable.

1.6 Approach

In quantifying the extent of water loss in GCs within three selected water distribution systems, the following steps were identified for execution:

1. A comprehensive literature review pertinent to the following:
   a. Components of urban water consumption, focusing predominantly on residential water consumption,
   b. Standard Water Balance with the respective components and associated terminology,
   c. Water leakage and the means by which the component is defined, and
   d. Specific studies on GCs and the findings thereof.
2. Define, within the methodology, the process undertaken for:
   a. The collection of datasets following a stringent categorisation and selection process,
   b. The verification of flow rates in relation to the Council for Scientific and Industrial Research (CSIR) 2019 and previously published studies,
   c. The consolidation of the night flow registers used in determining the MNF and the current annual real losses (CARL),
   d. The estimated unavoidable annual real losses (UARL) in connection to the selected distribution systems, and
   e. The establishment of the infrastructure leakage index (ILI) in accordance with each GC.
3. Obtain and consolidate a data catalogue of flow rates from GCs following the above mentioned criterion.
4. Analyse the total water loss by means of flows sourced from the MNF period and formulated via a statistical approach.
5. Investigate the ILI ratios in relation to the proportioned UARL and CARL values for an indicated average operating pressure (AOP) range.

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6. Critically evaluate the findings and provide possible contextual commentary on the results.
7. Critically evaluate the usefulness of the research and offer recommendations for future work.

1.7 Motivation

Although an extensive amount of research has been done and published worldwide in assessing the extent of real losses in water networks, little has been done to address water leakage and losses within GCs. The provision of added security and lifestyle improvements has resulted in a gradual rise in the number of GCs as more consumers feel the urge to relocate from freestanding properties (Thuillier, 2005; Genis, 2007; Woo and Webster, 2014 and Tedong *et al.*, 2015). According to Lugoma *et al.* (2011), distribution systems in GCs are well maintained and self-managed for which municipal authorities are not held accountable for the network infrastructure. Consequently, there is a growing need in further research to better understand the extent of real losses within the systems as they differ from the rest.

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2. Literature Review

Presented in the chapter is a review of relevant literature sourced from various scientific journals, thesis reports, stipulated guidelines in addition to several published articles. The purpose of the chapter is to contextualise current information and develop a background in residential water loss in an attempt to answer the question posed in the aforementioned problem statement.

2.1 Components of urban water consumption

Residential water use encompasses cooking, cleaning, human consumption, personal hygiene and garden irrigation (Memon and Butler, 2006) and are amongst the most important uses of water. Household consumption can be split into indoor and outdoor end-uses such as the indoor and outdoor tap (Du Plessis *et al.*, 2018). Other components of urban water consumption include the industrial and commercial sectors which involve the fabrication, processing, washing, diluting, cooling, sanitation and transportation (Kebai *et al.*, 2019). Additionally, business, municipal and sporting facilities fall within the urban water consumption bracket.

2.2 Standard Water Balance

The International Water Association (IWA) has established a number of pertinent concepts in an attempt to promote a standardised international approach to the definition, assessment, monitoring and management of non-revenue water (NRW) and water losses. Various terms relating to water leakage and water loss were adopted by Pearson (2019). The IWA water balance is described in more detail by Couvelis and Van Zyl, (2015); Frauendorfer and Liemberger, (2010) and Trow and Farley, (2003).The total volume of treated water that enters into the section of the water distribution system is called the system input volume (SIV).

NRW includes the summation of all components that are not billed such as unbilled authorised consumption, apparent losses and real losses and as a result no income is derived (Pearson, 2019). The IWA Task Force recommendations provide the clarification and guidance on several pressing issues regarding the on-going problems faced in

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quantifying the extent of water loss and thus, can evaluate the effectiveness of water management (Lambert, 2002).

The international report commences with the IWA standard water balance and definitions, as the basic but essential first steps of any Water Conservation (WC) and Water Demand Management (WDM) programme. Furthermore, highlighting the extent of NRW and any potential shortcomings associated with the water balance components (Meyer, 2018). The IWA volumetric water balance was modified by Seago and McKenzie (2007) for South African conditions. Figure 2-1 provides a breakdown of the SIV into the different components of consumption and water losses. In order to ensure consistency of assessment and reporting of losses throughout the research, a brief description of the terminology associated with the water balance and the respective definitions of the components are provided.

<table>
<tr><td rowspan="9">System Input Volume</td><td rowspan="4">Authorised Consumption</td><td rowspan="2">Billed Authorised Consumption</td><td>Billed Meter Consumption</td><td rowspan="2">Potential Revenue</td><td>Free Basic Water</td></tr>
<tr><td>Billed Unmetered Consumption</td><td>Recoverable Revenue</td></tr>
<tr><td rowspan="2">Unbilled Authorised Consumption</td><td>Unbilled Meter Consumption</td><td rowspan="7" colspan="2">Non-Revenue Water</td></tr>
<tr><td>Unbilled Unmetered Consumption</td></tr>
<tr><td rowspan="5">Water Losses</td><td rowspan="2">Apparent Losses</td><td>Unauthorised Consumption</td></tr>
<tr><td>Customer meter inaccuracies</td></tr>
<tr><td rowspan="3">Real Losses</td><td>Leakage on transmission and distribution mains</td></tr>
<tr><td>Leakage on overflow from storage facilities</td></tr>
<tr><td>Leakage on service connections</td></tr>
</table>

Figure 2-1: IWA water balance (Seago and McKenzie, 2007)

2.2.1 Authorised Consumption

Pearson (2019) clearly defines authorised consumption as “The volume of metered and/or unmetered water taken by registered customers, the water supplier and others who are implicitly or explicitly authorised to do so by the water supplier for residential, commercial, municipal and industrial purposes”. Note, authorised consumption includes water utilised by the military and government for events such as fire-fighting, flushing of mains, watering of municipal gardens and street cleaning (Vermersh *et al.,* 2018). The aforementioned water volumes may be billed or unbilled, metered or unmetered.

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2.2.1.1 Billed Authorised Consumption

Billed authorised consumption is considered as a relatively crucial component within the water balance. Revenue gained is allocated to maintaining and improving the water network infrastructure in addition to ensuring water security and reliability of supply (Raymer and Tsatsire, 2018). The component of authorised consumption which is billed and produces revenue is equated to the summation of billed metered and billed unmetered consumptions, also known as revenue water (Pearson, 2019).

As discussed previously in section 2.1, residential water use can be separated into indoor and outdoor water consumption. Indoor consumption is the amount of water used by all water consuming appliances within the household/dwelling. Typical of such appliances are the toilet, bath, shower, dishwater, washing machine and any and all indoor taps (Knox, 2020).

Previous studies have shown that indoor water consumption patterns remain relatively constant, with little to no evidence of seasonal fluctuation (Mayer *et al*., 1999; Roberts, 2005; Beal *et al*., 2010). Consumption levels are generally related to the demographic, socio-economic and behavioural habits of the residents in addition to the type and efficiency of indoor appliances (Makki *et al*., 2015). The main factors influencing indoor use include: household size and income level (Bennett *et al*., 2012 and Makki *et al*., 2015).

Outdoor water consumption generally includes garden irrigation, water for refilling swimming pools, outdoor water features and any and all outdoor taps. Studies have reported various influencing factors in the type of consumption, including: garden area (Harlan *et al*., 2017), vegetation type (Wentz and Gober, 2007), irrigation methods (Roberts, 2005), size of swimming pool (Domene and Saun, 2006), climatic variables (Gato *et al*., 2007) and income level (Van Zyl *et al*., 2008 and Lowry *et al*., 2011). Outdoor water consumption is predominantly driven by climatic variables, which cause the seasonal fluctuation in consumption patterns (Roberts, 2005).

2.2.1.2 Unbilled Authorised Consumption

Unbilled authorised consumptions (UAC) comprise legitimate water usage, but are not billed and therefore, do not produce revenue. UAC is the summation of unbilled metered and unbilled unmetered consumption (Lambert, 2003).

UAC is often overlooked when approximating the NRW component within the standard water balance and may lead to the misevaluation of the apparent and real losses. Two categories are classified when defining UAC, namely servicing water and free water supply (Van Zyl, 2014). Servicing water, common to all water utilities, encompasses the volume of water used for operational purposes such as pipe flushing, tank cleaning, and hydrant flow and pressure tests. Free water supply is defined as the total volume of water that is provided to certain categories of consumers at no cost. Dependent on contractual agreements with customers or local authorities as the water utility may be privately, municipally or nationally owned (Vermersh *et al.*, 2018). Cleaning of sewerage facilities, drinking fountains, fire-fighting and street cleaning and others, fall within the free water supply bracket.

Table 2-1 summates the maximum defaults identified through international data and publications for which approximations of UAC are expressed as a percentage of water supplied.

Table 2-1: Recommended defaults for UAC (Vermersh *et al.*, 2018)

Source Country of Default Assessment	Unbilled Authorised Consumption Year or Source of Data	Expressed as a percentage of Water Supplied
23 England & Wales Companies: analysis of The Water Service Regulation Authority (OFWAT) published data	2002 - 2003	0% to 2.5% Median 1.25%
WSAA: Water Services Association of Australia	2009 - 2010	0.50%
New Zealand Water & Wastes Association	2010	0.50%
European Union 'Good Practices on Leakage Management' quick	2015	0.5% of Billed Metered Consumption
North America: American Water Works Association (AWWA) M36 Manual, 4th Edition, Water Audits and Loss Control Programs	2016	1.25%

2.2.2 Water Losses

The water loss component consists of real losses (RL) and apparent losses (AL) and is the difference between the SIV and the authorised consumption (Pearson, 2019).

2.2.2.1 Apparent Losses

Apparent loss (AL) is defined as having four contributing key factors, namely meter reading errors, water theft, meter under-registration and water accounting errors. Categorized as a loss to the municipality, the aforementioned components are consumed and can act and interact interchangeably (Rizzo *et al.*, 2007).

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A study undertaken by Rizzo *et al.* (2007) found that AL was not only multidimensional, but also dynamic in nature. In an attempt to resolve the abovementioned complexities, an integrated AL strategy was recommended for implementation by water utilities. Figure 2-2 is an example of several aids that a strategy may include for which the basis is targeted towards the concept of change.

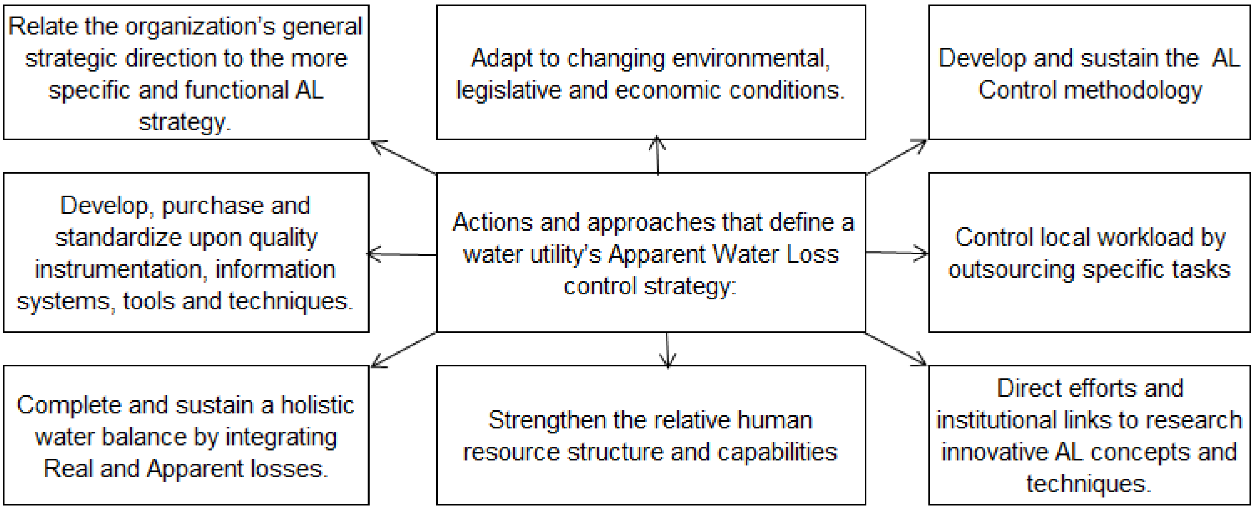

Figure 2-2: Apparent Loss Strategy (Rizzo *et al*., 2007)

The Water Research Commission initiated a study to assess the levels of leakage in accordance to 30 water utilities spread throughout South Africa (Seago *et al.*, 2004). Based on the research undertaken, a more pragmatic and realistic approach in approximating AL for typical water distribution systems was found as shown in Table 2-2.

Table 2-2: Approximation of AL (Seago *et al*., 2004)

Illegal Connections		Meter Age and Accuracy			Data Transfer	
			Good water quality	Poor water quality		
Very high	10%	Poor > 10 years	8%	10%	Poor	8%
High	8%					
Average	6%	Average 5-10 years	4%	8%	Average	5%
Low	4%					
Very low	2%	Good < 5 years	2%	4%	Good	2%

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2.2.2.2 Real Losses

Real loss (RL) reflects the physical water loss from a water distribution system up to the point of supply together with leakage from the pressurised system and overflow from the utility's service reservoir (Pearson, 2019).

RL can be estimated in different sectors of the water distribution system by comparing the readings from a bulk meter with the sum of the volumes through all consumer water meters. Nonetheless, if readings cannot be attained via the bulk and individual consumer meters, an analysis of the MNF in the DMA can be performed. Leak detection and pipe replacement initiatives can then be implemented for the most problematic zones (Van Zyl, 2014). The reduction in RL is achieved through four key actions, specifically active leakage control, pressure management, speed and quality of repairs and pipeline renewal, as shown in Figure 2-3.

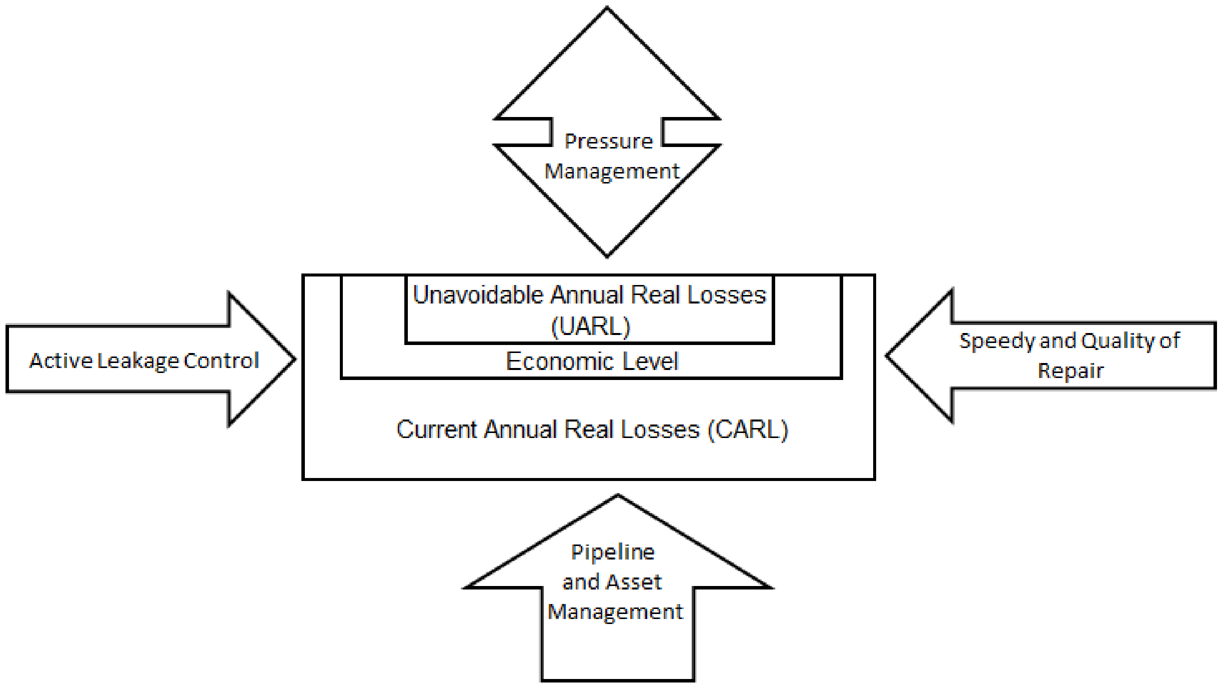

Figure 2-3: Key factors in reducing real losses (Pearson, 2019)

Active leakage control is the process of actively finding and repairing leaks within a water distribution system on a targeted or regular basis in an attempt to manage leakage. Leak detection techniques include leak noise correlators, pressure zero tests, ground penetrating radar and gas injections (Pearson, 2019).

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Pressure management allows pressures within a water distribution system to remain within an acceptable range in relation to the minimum required levels. Therefore, leading to the reduction in pipeline failure rates, water losses and wastage as well as prolonging service lives (Lambert *et al.*, 2013). The procedure in the speed and quality of repairs is to ensure that leak durations are minimised without reoccurrence. Pipeline renewal addresses the refurbishing or replacing of pipes that show a greater risk of disruption of services as well as potential increase in losses.

A note should be taken in differentiating water loss and water leakage. The IWA has defined water loss as the summation of RL and AL for which RL comprise leakage from pipes, joints, fittings and overflow. Water losses occur in all distribution systems. However, the volume of loss varies and is dependent on the characteristics of the system, the operational practices in addition to the level of expertise and technology applied in controlling it (Farley and Trow, 2003). RL can be severe and go undetected for several years during which the extent of the loss is reliant on the characteristics of the distribution system, leak detection and repair policy practices.

2.3 Water Leakage

Leakage is defined as water lost on a residential property, downstream of the customer's water meter (Couvelis and Van Zyl, 2015). The quality and age of infrastructure and water-using appliances along with the pressure of the reticulation system can influence leakage in terms of likelihood, frequency and volume (Saghi and Aval, 2015). The attitudes and characteristics of residents can also affect the level of leakage such as maintenance affordability, type and age of water-using appliances, the ability to detect and repair leaks within the household as well as the awareness and level of care of the residents (Trow and Farley, 2004).

Onsite leakage has been investigated by many researchers. However, the component is site specific and therefore relatively difficult to estimate (DeOreo et al., 1996).

In South Africa, McKenzie (2002) reported on the reduction in water consumption achieved through the implementation of plumbing replacement initiatives. Leakage was found to vary between 20 and 35 % based on projects in Kagiso, Tembisa and Hermanus. Similarly, a project in Munsieville in Mogale City found leakage to be 38 % of the total consumption according to the reductions in MNF (Alliance to Save Energy, 2006). Strategic leakage management is the process of managing leakage through measurement, monitoring,

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prioritising detection and leakage detection itself. Consequently establishing an optimum balance of activities in an attempt to secure reliable supplies or to avoid intermittent supplies (Pearson, 2019)

2.3.1 Unavoidable Annual Real Losses

The total volume of UARL signifies the lowest achievable volume for a well maintained and well managed distribution system. Tested and developed by the Water Loss Task Force for individual systems, the UARL can be determined from four key system-specific factors represented in Equation 2-1. Factors signifying background leakage, leakage from reported and unreported leaks in addition to pressure/leakage rate relationships (Hamilton *et al.*, 2006).

$$UARL\left({}^{L}/_{d}\right) = AOP(18Lm + 0.8Nc + 25Lp) \qquad \text{Equation 2-1}$$

Where:

Lm Length of mains including all pipelines, except service pipes (km),

Nc Number of connections,

Lp Length of private service pipe between property boundary and customer revenue meter/notional point of delivery (km), and

AOP Average operating pressure when system is pressurised (m).

In most urban developments, the individual consumer meter is at the property boundary and as a result, the length of the private service pipe (Lp) is considered nil (Pearson, 2019). Furthermore, background leakage is influenced by pipe materials, quality of installation, soil properties as well as pressure (Fox, 2016). Background leakage denotes the summation of all small leaks that persist with flow rates too low to be detected by any active leak detection and control initiative, unless discovered by chance or until a leak progressively worsens to a point of discovery (Pearson, 2019).

A study was performed by Lambert *et al.* (1999) in which components of UARL for different sectors of infrastructure were analysed. Based on previously published international data, presented in Appendix A1, Equation 2-1 was used to approximate the minimum background losses, typical burst flow rates and frequencies for distribution systems in good condition.

Although not all systems would typically experience the same burst frequencies and flow rates assumed in Appendix A1, attention should be drawn to the various UARL values

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illustrated in Table 2-3. Lambert *et al.* (1999) showed that the background loss component dominated the calculations. Furthermore, a sensitivity analysis performed on the assumptions made with regards to the 'bursts' components proved to have relatively little influence on the overall UARL.

According to Lambert *et al.* (1999), Table 2-3 provides a rational yet flexible basis for predicting the total UARL values for a variety of distribution systems. Previously published articles have highlighted that wide ranges in local key factors and limiting constraints experienced internationally have limited the application to situations located outside certain regions of origin. In the USA, values for UARL range between 2.4 and 7.1 m^3/km/d (AWWA, 1998). Germany records UARL values ranging from 1 to 5 m^3/km/d (Managing Leakage Report B, 1994) depending on ground type whereas, France have recorded values ranging from 1.5 to 7 m^3/km/d for rural and urban situations (Agence, 1990).

Table 2-3: Typical UARL values (Lambert *et al*, 1999)

Infrastructure Component	Background losses	Reported bursts	Unreported bursts	UARL total	Units
Mains	9.6	5.80	2.60	18	L/km mains/day/m of pressure
Service connections, meters at edge of street	0.6	0.04	0.16	0.8	L/conn/day/m of pressure
Underground pipes between edge of street and customer meters	16	1.9*	7.1*	25	L/km u.g. pipe/day/m of pressure

* Assuming an average length of 15m/connection

The UARL approach, presented in Equation 2-1, has the advantage in which specific values for each distribution system is considered.

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2.3.2 Current Annual Real Losses

The current annual real loss (CARL) is the current best estimate of the average real losses over a year (Pearson, 2019). The minimum night flow (MNF) is often used as an indication of the real losses. The MNF, typically measured in m^3/h, is the minimum one hour flow rate recorded during the early morning period. According to Pearson (2019), the time frame is normally defined between the hours of midnight and 6 am, though urban situations specify a more distinct period between 2 and 4 am. Furthermore, the MNF is denoted as the most viable piece of data as far as estimating night leakage is concerned. In controlling water leakage and loss in water networks, pertinent domain knowledge is required in understanding how the system's components interrelate. The MNF method establishes relatively strict criteria for approximating the factors related to water losses as most consumers are not 'active' during the night. Consequently, consumption levels can be more easily obtained. Note, minimal fluctuation in consumption occurs during the MNF period. However, due to seasonality and household, commercial and industrial activity, consumption levels vary during the day (Gomes *et al.*, 2011). Tracking over a period of time aids in identifying any unreported leakage accumulating in the specific area making the MNF the key activity in leakage management (Mutikanga *et al.*, 2013). For the duration of the MNF, while consumption levels continue to fall, leakage however is at a maximum proportion of the total flow within the water distribution system (Pearson, 2019), as shown in Figure 2-4.

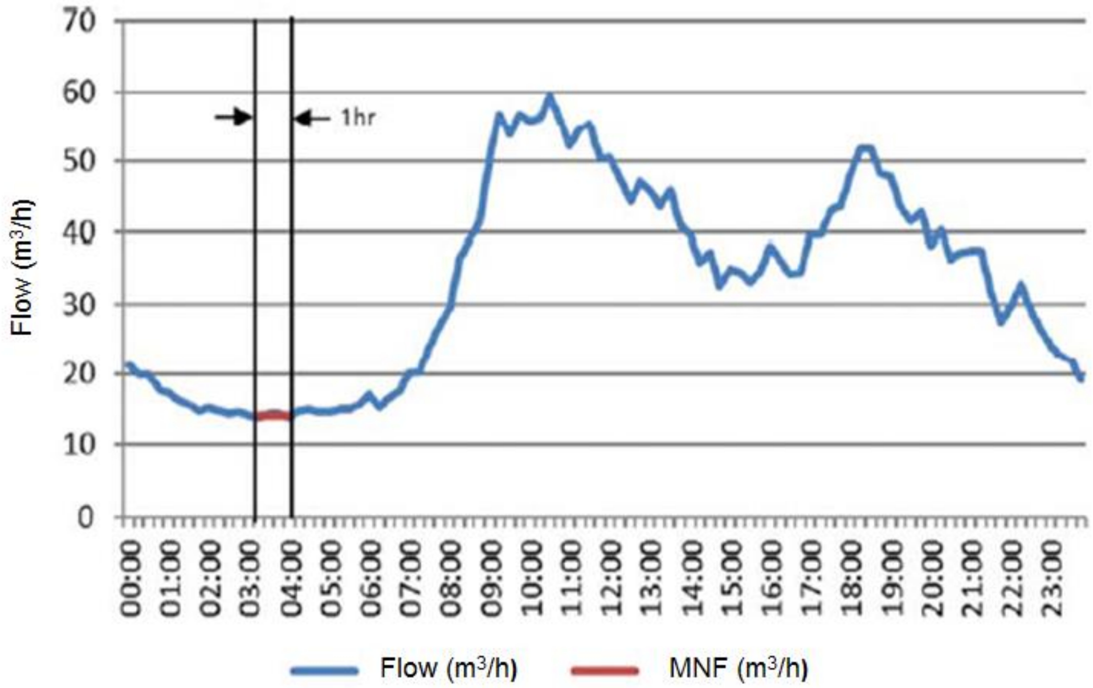

Figure 2-4: Extract of the MNF period (Pearson, 2019)

A study involving several specialists from UK's top leading water companies was conducted over a four year period. In so doing, the specification of the terminology and recommendation of procedures to the most feasible method in approximating each loss component and consumption were defined (Gomes *et al.*, 2011). The abovementioned study is published across nine reports known as the Managing Leakage Reports (WRC 1994). During the course of the Managing Leakage Report series, new empirical concepts were established in assessing various contributing factors effecting real night losses. In this context, Lambert (1994) proposed a methodology denoted as Bursts and Background Estimates (BABE) for a specified reference flow rate. Similarly, May (1994) presented the Fixed Area and Variable Discharges (FAVAD) power function method for real water networks. Based on the resultant concepts, BABE, FAVAD and others, a number of models were derived in aiding towards an improved management and control of water losses. These concepts are described in more detail by (McKenzie and Langenhoven, 2001; Fantozzi and Lambert, 2007; Awad *et al.*, 2008 and Giustolisi *et al.*, 2008 a, b). Sourced from the Water Research Commission (1994) are the typical default MNF parameters when approximating each loss component and level of consumption, as shown in Table 2-4.

Table 2-4: Default MNF values (WRC, 1994)

Losses downstream of delivery point (at 5 bar)	0.5	L/con/hr
Minimum domestic night flow (pressure-independent)	8	L/consumer/hr
Minimum domestic night flow (pressure-dependent)	2	L/consumer/hr
Percentage of active population	6	%

Equation 2-2 is used to approximate the leakage component, commonly referred to as the CARL, during the time the MNF is assessed.

$$CARL = MNF - LDNC \qquad \text{Equation 2-2}$$

Where:

CARL Current annual real losses (L/s),

MNF Minimum night flow (L/s), and

LDNC Legitimate domestic night consumption (L/s).

By subtracting the LDNC from the MNF, an estimate regarding the CARL for a specific district metered area (DMA) can be obtained (Mutikanga *et al.*, 2013). The LDNC takes into account plumbing losses along with actual authorised customer uses during the period of MNF and therefore needs to be taken into consideration (Pearson, 2019). LDNC, usually expressed in the form of l/prop/h, is largely consistent and is generally estimated from data sourced from a statistical sample of domestic users (Fanner *et al.*, 2015).

A diagrammatic representation of Equation 2-2 is illustrated in Figure 2-5. The MNF method cannot typically be used for systems with intermittent water supplies or systems containing service reservoirs as the system may be shut off or depressurised leading to little and/or no leakage at that time (Washali *et al.*, 2018).

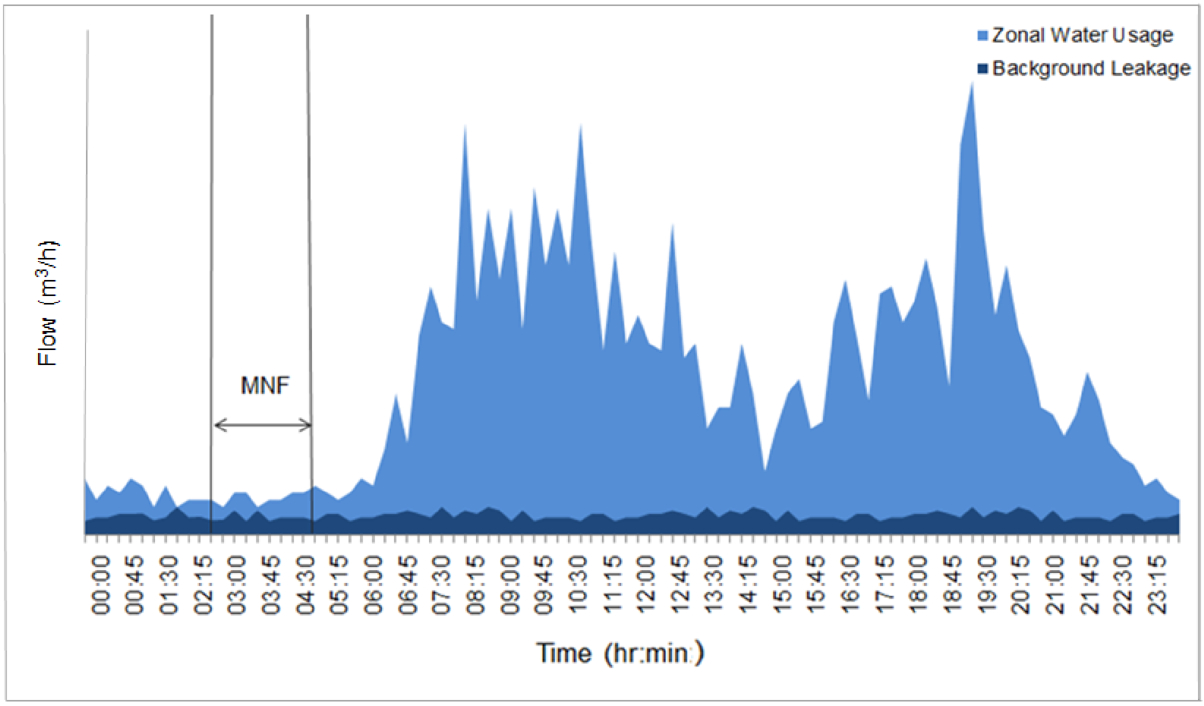

Figure 2-5: Components of MNF

The component of CARL approximated during the MNF becomes sensitive when establishing levels of LDNC. According to Fanner *et al.* (2015), the majority of water utilities relied on a default LDNC value of 1.7 L/prop/h. However, the uses of national default figures are no longer considered acceptable unless based on DMA specific data. In practice, the process in determining the LDNC directly from DMA data becomes flawed as nightlines also include legitimate non-household night consumption (LNHHNC).

In an attempt to better understand the component of LDNC, Bristol Water comprised data from small consumption monitor areas (CMAs). A study published by Fanner *et al.* (2015) used a statistical approach to analyse LDNC based on data sourced from Bristol Water. Table 2-5 illustrates an extract of the findings pertinent to the aforementioned study for which the complete table can be found in Appendix A2. Certain CMAs were analysed more than once as to evaluate the seasonal variation in LDNC. Fanner *et al.* (2015) found that the data collected exhibited significant variability, both at the same CMAs over time as well as between CMAs falling within close proximity of one another.

Table 2-5: Recorded LDNC from CMAs (Fanner *et al*., 2015)

CMA No.	Site Name	No. of Props	No. of Days	LDNC (L/prop/h)
4045	Tickenham	218	38	5.79
7022	Bishop Sutton	284	42	7.75
1094	Wickwar	188	55	2.77
2131	Little Stoke	275	24	3.13
2131	Little Stoke	275	49	5.15
1133	Frampton	268	40	2.74
1138	Winterbourne	188	41	7.84
8310	Weston	89	35	1.82
8310	Weston	89	33	1.99
8311	Hotwells	132	31	1.55
8311	Hotwells	132	29	2.12
8313	Clutton	114	44	1.37
8319	Hartcliffe	111	29	1.52
2275	Eastville	482	27	3.36
2275	Eastville	482	25	4.39
3112	Totterdown	670	25	3.75
3174	Southville	887	33	8.07
2277	St Werburghs	416	47	4.26
3416	Lawrence	616	40	5.02
8324	Kingswood	182	30	2.68
2332	Hillfields	705	32	3.32
3101	Knowle	853	32	4.75
8325	Hortfield	111	40	1.8
8325	Hortfield	111	46	4.62
Total		12004	789	Average 3.69

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A study conducted by Water New Zealand (Taylor, 2017) showed to some extent, the on-going issues in managing water losses as published in the National Performance Review (NPR). The NPR comprised 49 water utilities supplying water to 90 % of the population. Collectively, the approximated CARL between the years of 2015 and 2016 amounted to 100 000 ML, enough to fill over 40 000 Olympic sized swimming pools.

2.3.2 Infrastructure Leakage Index

The total annual water loss becomes an effective indicator concerning the efficiency of water distributions, both in individual years as well as apparent trends developing over a period of several years. High or increasing water losses highlight ineffective planning and construction in addition to low operational maintenance activities (Hamilton *et al.*, 2006). The infrastructure leakage index (ILI) is a measure of how well a water distribution system is able to be managed, maintained, repaired and rehabilitated in regards to the control of real losses, at the current operating pressure (Lambert *et al.*, 1999). The ILI is the ratio of CARL, the most viable estimate of the average real losses over a year, to the value of UARL calculated for current operating pressures and continuity of supply. The non-dimensional performance indicator, illustrated in Equation 2-3, specifies the current overall management of the water network infrastructure for leakage control purposes (Taylor *et al.*, 2008).

$$ILI = {}^{CARL}\!/_{UARL} \qquad \text{Equation 2-3}$$

Where:

ILI Infrastructure leakage index (dimensionless),

CARL Current annual real losses (L/s), and

UARL Unavoidable annual real losses (L/s).

Since ILI is dimensionless, comparisons between countries that use different units of measurement are enabled. The greater the amount by which the ILI exceeds 1.0, the higher the need for further management of real losses via the controlling and maintenance of the system infrastructure. Additionally, a more intensive active leakage control as well as an improved effectiveness and efficiency of repair times can be implemented (Lenzi *et al.*, 2013).

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According to Lambert and McKenzie (2002), the ILI is proving to be the most useful and practical performance indicator, measuring the combined performance of the operational management approaches for RL. With reference to Figure 2-3, active leakage control, pipeline management as well as the speed and quality of repairs fall within the bracket.

A data set comprising 27 diverse distribution systems, spread across 20 countries, were assembled by the IWA Water Losses Task Force. All distribution systems consisted of relatively reliable recordings and active policies in an attempt to conceptualise and manage RL (Lambert *et al.*, 1999). Presented in Figure 2-6 are the findings in accordance to the study undertaken in which ILI values ranged from 0.7 to 10.8.

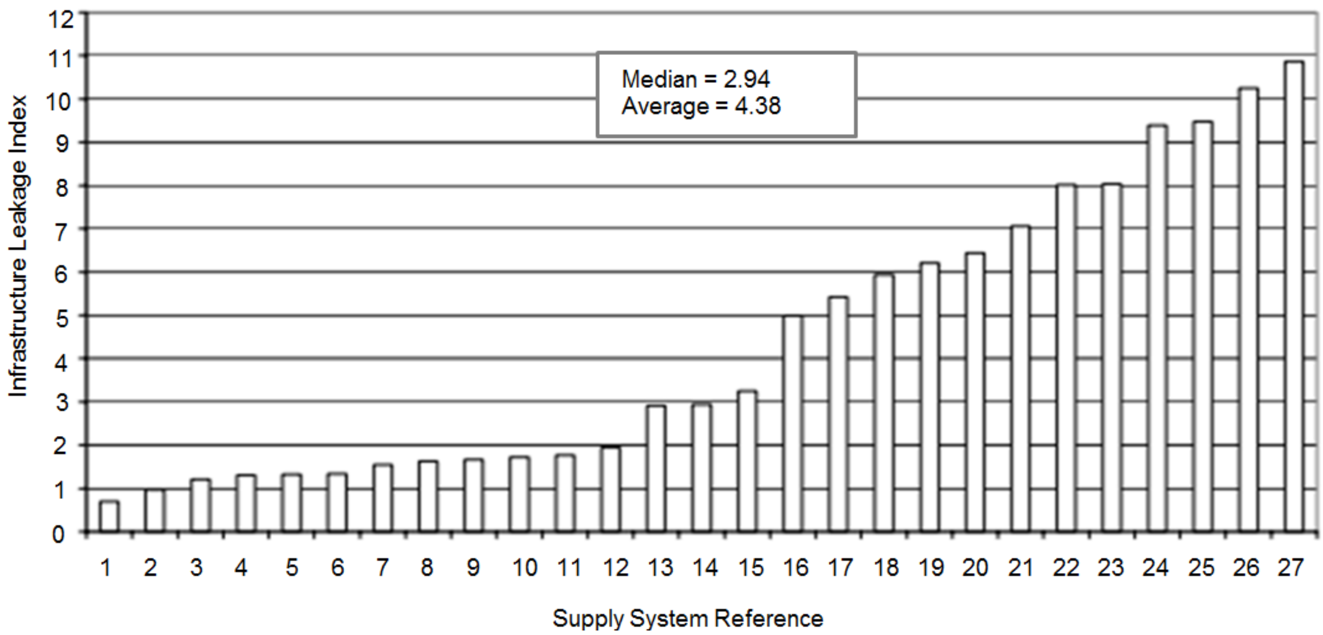

Figure 2-6: ILI case study (Lambert *et al*., 1999)

Since 1999, numerous studies have further addressed the ILI for distribution systems in more than 40 countries (Carpenter *et al.*, 2002; Lambert *et al.*, 2001 and McKenzie *et al.*, 2002). Liemberger (2002) recorded values far higher, in excess of 100, for individual distribution systems in poor condition.

Note, the ILI does not take into account economic factors and is purely a technical performance indicator.

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According to Winarni (2009), there becomes a level of leakage in which a further reduction would no longer be cost effective and so, no financial incentive. Moreover, Liemberger (2002) showed that water losses as a percentage of SIV did not necessarily reflect poor water loss management. In Table 2-6, the 10 best performing utilities in terms of ILI are compared to the respective CARL from which no correlations could be drawn.

Table 2-6: ILI vs. CARL (Liemberger, 2002)

Utility	Country	ILI	CARL, % SIV
Ecowater	New Zealand	0.9	9.1
Water Board of Lemesos	Cyprus	1	12.5
Wide Bay Water	Australia	1.2	11.5
Malta WSC	Malta	1.6	19.7
SA Utility 13	South Africa	1.8	9.7
Bristol Water Plc	England	1.9	16.8
SA Utility 20	South Africa	1.9	6
SA Utility 6	South Africa	2.6	7.6
Charlotte County Utilities	USA	3.1	24.2
SA Utility 26	South Africa	3.8	10.2

The case study conducted by Seago *et al.* (2004), discussed in Section 2.2.2.1, reported on a number of components defined within the standard water balance. Table 2-7 highlights the records obtained in relation to the 30 water utilities located throughout South Africa. Seago *et al.* (2004) found a range of ILI values from 0.08 to 15.96 with a resultant average of 5.69. Note, utility No. 4 comprised of similar SIV and authorised consumption value which in result led to a suspiciously low 0.08 ILI value and is most likely incorrect. Furthermore, the study concluded with an average UARL of approximately 59.93 L/con/d, an average AL of 82.83 L/con/d as well as an average CARL of 340 L/con/d. AL was converted from m^3/y to L/con/d for comparative purposes.

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Table 2-7: Case study summation (Seago *et al.* 2004)

No.	Mains Length	Service con.	Density	Pressure	UARL	SIV	Authorised Consumption	AL	CARL	ILI
	km	no.	no./km	m	L/con.d	10^3 m^3/yr	10^3 m^3/yr	10^3 m^3/yr	10^3 m^3/yr	
1	718	31200	43	50	61	22039	17134	981	3924	5.68
2	1069	60208	56	40	45	24344	9583	2952	11809	12.12
3	1315	79306	60	50	55	30284	25362	984	3938	2.48
4	762	52928	69	45	48	19179	19089	18	72	0.08
5	2400	198951	83	60	61	83788	71948	2368	9472	2.14
6	35	1156	33	51	69	760	566	29	165	5.68
7	38	1142	30	63	88	1110	940	26	145	3.93
8	678	44550	66	50	54	34739	17323	3832	13584	15.56
9	456	21100	46	50	59	12043	8965	616	2462	5.38
10	27	557	21	35	59	250	203	7	40	3.36
11	2082	75059	36	75	97	135687	98616	7354	29417	11.02
12	28	1017	36	40	52	1419	1391	6	22	1.16
13	103	5872	57	50	56	3654	3113	108	433	3.62
14	1552	94105	61	50	55	52389	40999	2278	9112	4.84
15	1275	69000	54	50	57	36353	27159	1839	7355	5.21
16	321	22700	53	50	57	11505	5997	1322	4186	8.85
17	52	1478	28	35	50	742	594	22	126	4.65
18	746	29760	40	50	63	21603	8730	2575	10298	15.15
19	920	30786	33	70	94	18347	11814	1307	5226	4.97
20	358	10200	28	40	57	26976	24207	554	2215	10.39
21	467	21577	46	50	71	7257	6058	240	959	1.71
22	2390	112000	47	70	83	85020	66465	3711	14844	4.38
23	386	18931	49	45	53	12254	9992	339	1923	5.30
24	2943	191518	65	45	48	139685	113369	5299	21197	6.26
25	732	36253	50	35	41	39153	37103	410	1640	3.04
26	166	7817	47	40	47	2966	2377	118	471	3.49
27	1850	145000	78	45	56	69775	56863	2582	10330	4.21
28	263	12555	48	30	35	12019	10083	252	1684	10.41
29	353	11283	32	33	45	4427	3477	190	760	4.19
30	1571	97592	62	75	82	46218	36048	2034	8136	2.79

Table 2-8 shows typical ILI benchmark values for developing countries published by CSIR (2019).

Table 2-8: ILI benchmark values (CSIR, 2019)

Anticipated level of infrastructure leakage	Typical ILI range for developing countries
Excellent	1.0 - 4.0
Good	4.0 - 8.0
Average	8.0 - 16.0
Poor	> 16.0

Since the UARL takes pressure into consideration, the ILI is solely an indication of leakage detection and repair performance and thus, in stipulating the AOP associated with the ILI values, views can be taken as to whether an opportunity exists to undertake pressure management (Winani, 2009).

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2.4 Specific studies on residential estates

Worldwide, there is a growing need for the relocation from freestanding properties to GCs due to the added security and lifestyle improvements (Landman, 2004). The availability of amenities to support the consumptions of the residents, the improved management of infrastructure in addition to the implementation and adherence to the legislation pertinent to the GC remain the key factors for estate living (Spocter, 2011).

GCs are regarded as a benefit to municipalities and various reports indicate substantial growth in numbers worldwide over the past two decades (Thuillier, 2005; Genis, 2007; Woo and Webster, 2014 and Tedong *et al.*, 2015). Since 2005 there has been a steady increase in the authorisation of GCs, especially in the Western Cape Province (Spocter, 2011). Causes take account of the worldwide economic downturn and the establishment of the development guidelines stipulated by the South African Department of Environmental Affairs and Development Planning (DEADP). The DEADP released a guideline of objectives including sustainable development principles encompassing responsible water-use and effective storm water management planning.

A typical layout of a GC encompasses residential plots, communal roads, bulk and individual consumer meters in addition to mains and municipal pipelines. Although plots are privately owned, water users must adhere to the GC rules as well as municipal bylaws (Walks, 2014).

No clear guidelines have targeted the estimation of water consumption within GCs specifically (Trow and Farley, 2003). In most cases, potable water is supplied from a bulk water supply pipeline at a metered connection in which water supplied is metered and billed by the municipality. The costs are then cascaded to the consumers on an individual meter reading basis (Du Plessis, 2018).

Peak residential water demands serve as a valuable basis when analysing a water distribution system. The information enables the estimations of future water consumptions as well as an aid in the design, rehabilitation and sizing of supply components (Gato *et al.*, 2014). The Peak Factor (PF) is the ratio of the maximum flow to the average daily demand within the distribution system (Pearson, 2019). The AADD refers to the average annual daily water requirement of a consumer at the point of connection and is the total volume used by the customer for the entire year, divided by the number of days within the specified year. For design purposes, the CSIR (2019) stipulated standardised guidelines, presented in Table 2-9, when selecting and approximating the PF and AADD for different land uses.

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Table 2-9: CSIR (2019) guidelines required for the study

Land use		Water demand (AADD) kL/unit/d
Residential stands	High density, small sized	0.60 - 0.80
	Medium density, medium sized	0.8 - 1.00
	Low density, large sized	1.00 - 1.30
	Very low density, extra large sized	1.30 - 2.00
Predominant land use		PF (dimensionless)
Residential (RES)		3.6

The peak residential demand can then be approximated by means of Equation 2-4 for GCs A, B and C using the recommended values specified in Table 2-9.

$$\text{Peak Flow} = (\text{AADD}) \times (\text{N}) \times (\text{PF}) \qquad \text{Equation 2-4}$$

Where:

AADD Annual Average Daily Demand (L/s),
N Number of units, and
PF Peak Factor (dimensionless).

Du Plessis and Jacobs (2018) conducted a study on a consolidated catalogue comprising 2888 GCs located throughout South Africa. The monthly water use records were analysed. Results highlighted that water use for the aforementioned GCs were relatively low and fell within the 25th percentile according to other guidelines made available (CSIR, 2005; Jacobs and Haarhoff, 2004 and Van Zyl *et al*., 2008). Although the AADD was found to increase with plot size, compared to the previous publications, the AADD remained relatively low as depicted in Figure 2-7. Note, the regression lines presented are in accordance to the study regions pertinent to the Du Plessis and Jacobs (2018) study. According to Bekleyen *et al.* (2016), neighbourhood enhancements generally lead to an increased consumer awareness which would in result explain the higher water conservation and relatively lower water consumption. Therefore, the study confirmed that water use within GCs were notably dissimilar from previously published water use.

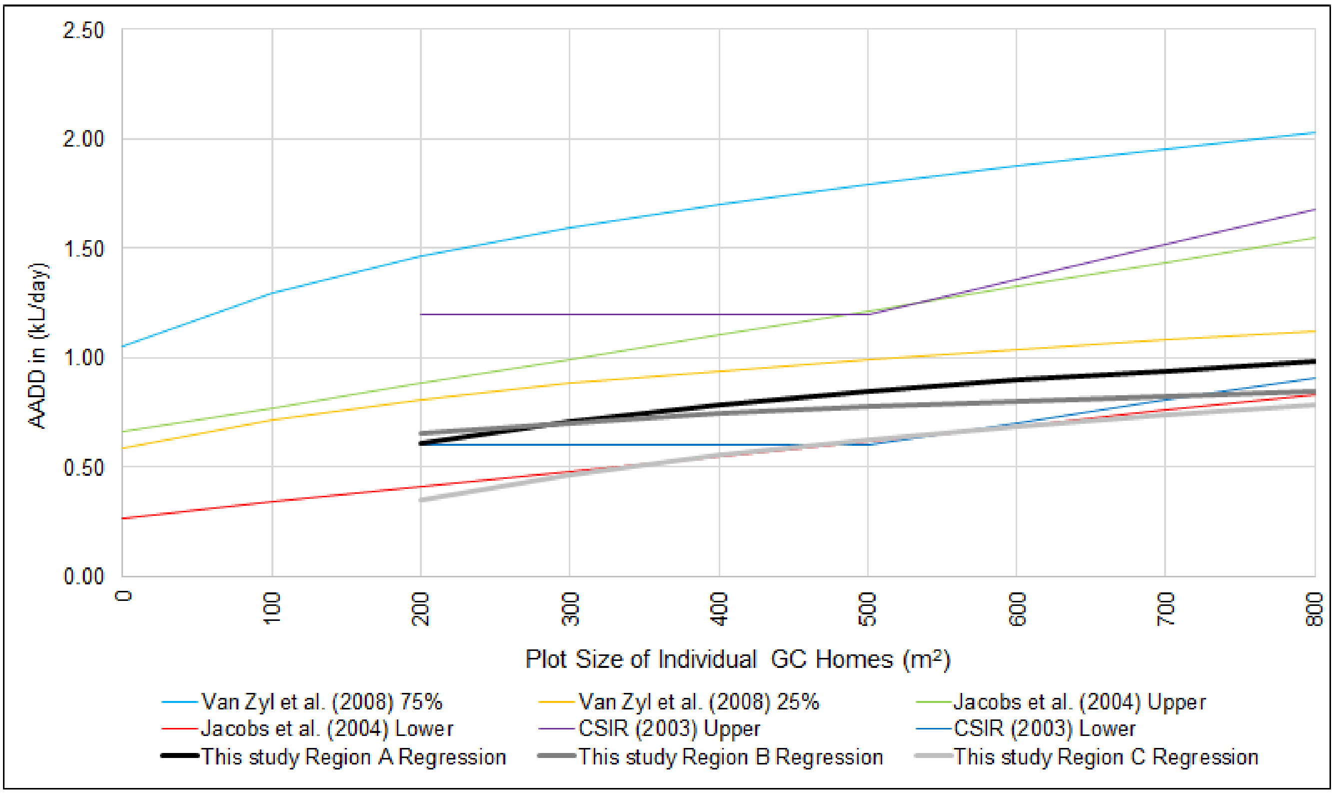

Figure 2-7: Comparison of data versus other guidelines (Du Plessis and Jacobs, 2018)

An extensive amount of research has been done and published worldwide in defining and approximating the components within the standard water balance. However, additional research focusing on assessing the extent of water losses, primarily real losses, within GCs would prove to be highly beneficial. For reasons previously mentioned, an increasing number of consumers feel the urge to relocate to GCs. Furthermore, the water shortcomings and associated abnormalities that endure within the Western Cape, lead to a growing need to better understand water losses within the well maintained and self-managed distribution systems. In doing so, improved mitigation strategies can be implemented towards Water Conservation (WC) and Water Demand Management (WDM) initiatives.

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3. Methodology

The chapter details the step by step methodology applied throughout the research subsequent to the contextualised published literature addressed throughout Chapter 2. The means in obtaining and preparing the datasets relevant to the question posed in the problem statement is explicitly defined. Furthermore, the techniques and procedures in analysing the abovementioned data are clearly stated.

3.1 Data Collection

A data record catalogue, comprising bulk meter flow rates collected at regular intervals of 15 minutes, was used for the research and sourced from Pinpoint Plumbing Leak Detection. Raw data was sourced via the implementation of the system Zednet.

Zednet is a web based software solution supplying data pertinent to the management of water loss and the monitoring of hardware installed at the specified distribution systems. Provided as a hosted service (Saas), raw data was aggregated from a range of logging devices, primarily via the Global System for Mobile Communications (GSM) for body cooperates and associations, municipalities, homeowners and insurance companies. Default support for measurements comprised flow rates, reservoir levels, borehole depths, pressures, rainfall, river gauging and water quality from which the raw data was filtered and adjusted to compensate for errors in calibration. An application programming interface (API) enabled third party access for which data was exported automatically. The assessment of ‘Live data’ allowed for the charting of multiple channels simultaneously as data was filtered for specific events/intervals. Moreover, the application of a user friendly document management and basic GIS functionality provided a high level map based view allowing quick overviews of the specified water networks.

The Zednet system and remote monitoring equipment is depicted in Figure 3-1. The system is able to connect to any water meter supplied with pulsed or GWFcoder technology for central readout. Transmission of the signal is based both on wireless communication (GSM) functionality and fixed net communication via Ethernet with glass fibre cables and/or power lines. Water meter readings were then relayed to a remote server, located in Kayamandi, Stellenbosch where the software was studied in detail so as to establish the means for the collecting, sorting and filtering of raw data.

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Raw data was initially exported from Zednet to a CSV file and later imported to Microsoft Excel post-extraction for the sorting and filtering process, further discussed in succeeding chapters.

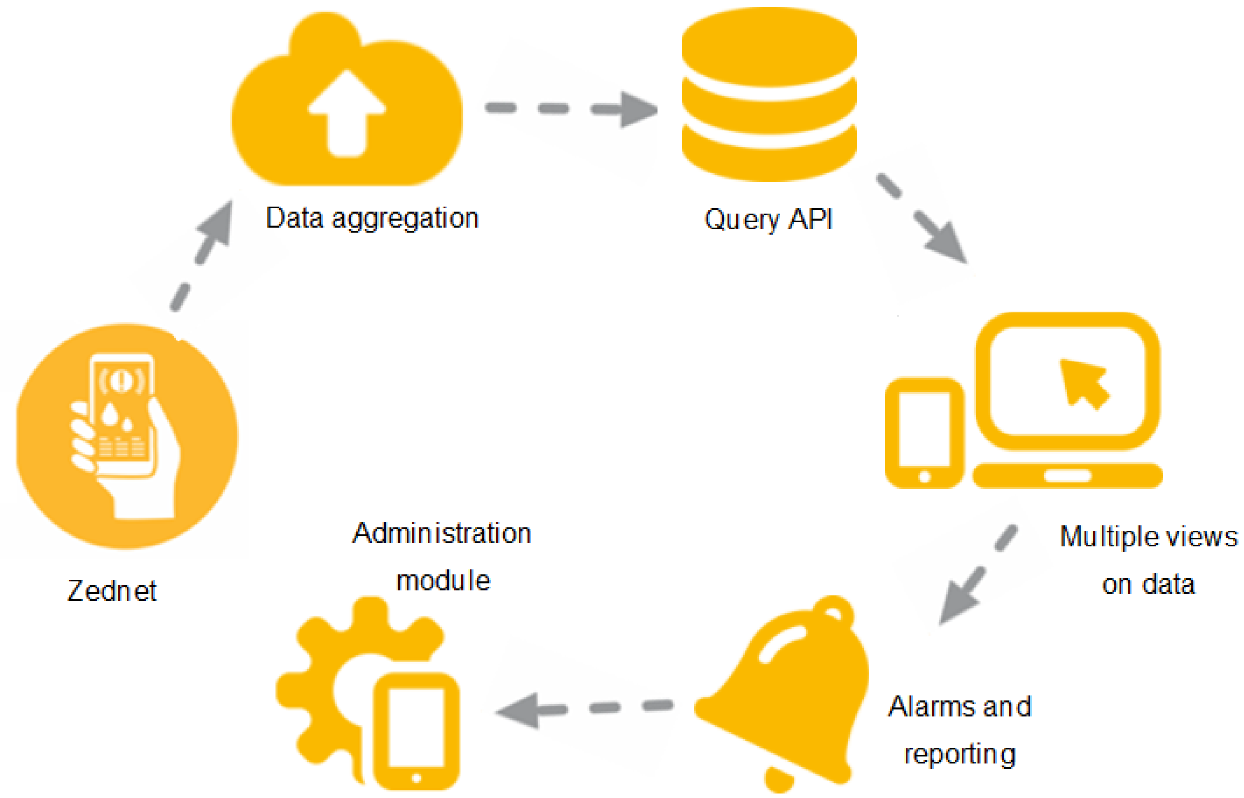

Figure 3-1: Schematic flow of the application of Zednet

Note, the application for ethical clearance was not a prerequisite for access to present personal clientele information was not permitted. Giurco *et al.* (2010) suggests potential privacy risks when addressing the level of detail of information made accessible to users. Households reporting minimal water consumption can be construed as vacant. Conversely, households consuming water in excess of the specified mandatory restrictions can be criticized as the reporting of trends highlighting abnormal water-use practices can stigmatize cultural ethnicities and/or locations.

As stated in Section 1.4.2, data sets comprised entirely from bulk meters as individual household readings were unobtainable. In order to preserve the integrity of the research and attempt to effectively address the problem statement posed in section 1.2, the following criteria were applied during the consolidation process:

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1. Phase 1 – Categorisation

    a. Due to the scope of the research and availability of data, flow rate records had to be recorded within the Western Cape Province,
    b. To maximize the accuracy in approximating the RL component within GCs, data sets had to be of at least 12 months long, and
    c. In following with the objectives stipulated for the research, data records had to be sourced from GCs.

2. Phase 2 – Selection

    a. As not to jeopardise the accuracy in the findings of the research, missing data/recordings had to be minimal. Note, as previously mentioned the research negates the necessity of predicting or expanding data records. A model was programmed to identify a varying range of consecutive no-flow readings logged throughout a single day with the exception of flow rates recorded during the MNF. Days having extended zero readings were omitted from the data set. The analysis implemented in quantifying the severity of no-flow readings throughout a single day is detailed in chapters to follow.

3.2 Data Verification

A verification process, Phase 3, was performed on the flow rates that successfully met the aforementioned criteria so as to confirm the data used was both feasible and fell within an acceptable range. The procedure was as follows:

1. The highest recorded flow rate within each GC database was compared with peak flow calculations based on the CSIR (2019) criteria by:

    a. Locating the actual maximum flow rate recorded, in L/s, for all specified GCs,
    b. Obtaining the appropriate guideline standards stipulated in the CSIR (2019) Redbook. In so doing, site specific data pertinent to the number of occupied units in addition to the approximated average plot sizes within GCs were denoted as prerequisites.
    c. Calculating the 15 minute peak flow rates based on the stated CSIR (2019) criteria, and lastly

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d. Assessing viable correlations so as to highlight any potential problematic areas.

2. The AADD/Plot size ratios were approximated for each selected GC and compared with the results found in the Du Plessis and Jacobs (2018) case study, discussed in Section 2.4, by:

   a. Calculating the actual AADD, in KL/d, for each GC,
   b. Plotting the aforementioned AADD with the previously obtained average plot sizes in accordance with Figure 2-8. and lastly
   c. Evaluating possible correlations between the GC database and the workings of Du Plessis and Jacobs (2018).

3.3 Establishment of water loss components

The research focuses exclusively on the extent of real losses within the selected distribution systems. In so doing, the analyses of components pertinent to the IWA water balance were necessary so as to verify and segregate the real losses. The components of water loss for GCs A, B and C were approximated for the duration of the night flow period by means of the following:

1. The consolidation of the night flow register comprising the 15 minute bulk flow rates. Night flows for each GC were further ranked and plotted collectively for comparative reasons. The average bulk meter night flows as well as an average household night flow approximation were further analysed within each site-specific water network.

2. The determination of the MNF sourced from the night flow register and defined as the lowest consecutive flow rate for the duration of one hour. A more stringent filter investigated no-flow recordings flagged adjacent to days removed during the initial selection process (Phase 2), focusing predominantly of flows recorded during the MNF period. Flows recorded throughout the night flow time frame were taken into consideration and omitted if deemed improbable. The MNF values were further ranked and correlated as a basis for the determination of the average bulk MNF in addition to the average household MNF.

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3. The implementation of Equation 2-1 for the determination of the UARL component associated with the system-specific input parameters. The numbers of occupied households were obtained from the results stated throughout Section 3.2. The length of mains (Lm) comprised the length of roads running adjacent to individual plots. Due to the average plot sizes, GCs A and B were subjected to the condition stipulated in Section 2.3.1 in which the length of the private service pipeline (Lp) was nullified. However, this would not be the case for GC C for which measurements were taken between the property line and the individual households. With the AOP constantly fluctuating for different water networks throughout the course of a single day, a pressure range of 30-50 m was chosen and deemed practical. Finally, values representative of the average UARL were tabulated according to the selected AOP range.

4. The calculation of the non-dimensional performance indicator ILI by means of Equation 2-3. In so doing, the component of CARL for the specified distribution systems were analysed via the utilization of Equation 2-2. With flow recordings sourced between the hours of 2 and 4 am, when consumption levels were minimal, the LDNC component was assumed to be minor and have little to no effect and consequently negated. The UARL values were proportioned to the CARL component so as to establish the ILI ratios for the range of operating pressures. ILI values were ranked and plotted so that potential correlations could be identified with regards to the AOP range as well as comparative connections between the specified GCs. By means of a statistical approach, the ILI averages for GCs A, B and C were found in accordance with the operating pressures.

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4. Data Collection and Verification

The chapter focuses on the categorisation, selection and verification processes performed during the consolidation of the data record catalogues used for the research. Although the chapter is aided through the utilization of extracts taken from tables, the length of the flow records prohibits the complete dataset from being presented in the Appendix.

4.1 Data Collection

As part of the research, a case study was included where data was collected from the field via the collaboration set up with Pinpoint Plumbing Leak Detection. Accredited by the Water Institute of Southern Africa (WISA) and the Building Industry Bargaining Council, Pinpoint has successfully completed individual onsite leakage tests in excess of 20 000. Raw data was sourced via the implementation of the system Zednet for which the schematic flow of process for the acquisition, capture, transfer and analysis of water flow data is presented in Figure 4-1.

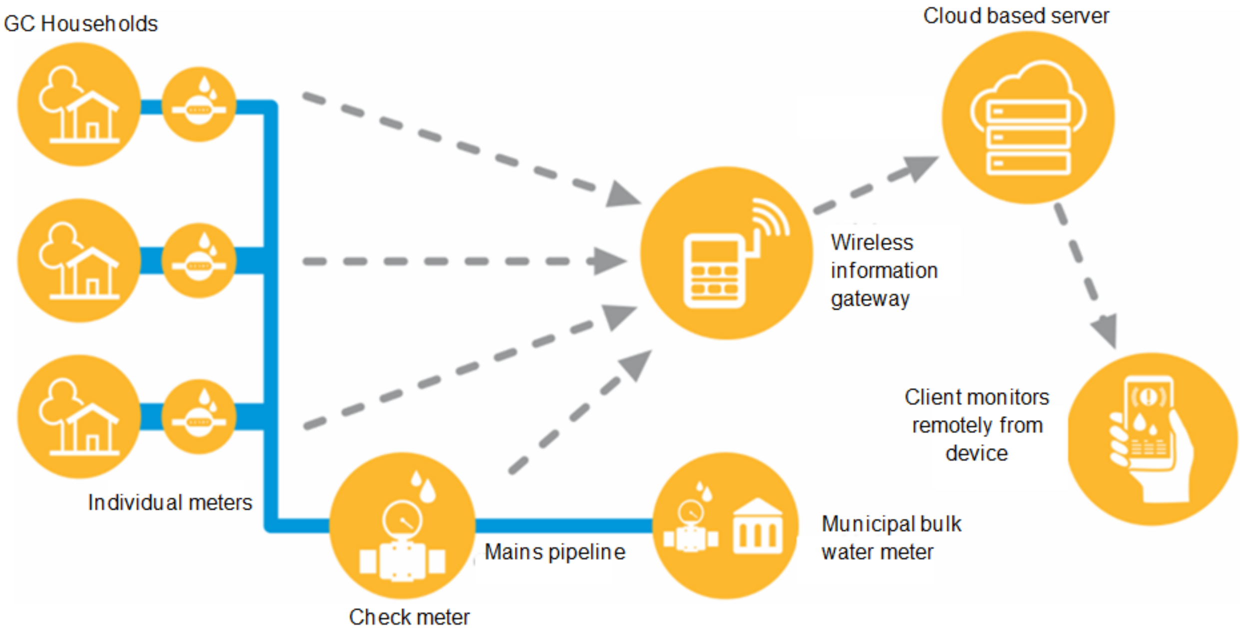

Figure 4 -1: Schematic flow of process for the collection of raw data

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The remote monitoring software Zednet was used to remotely access 15 minute water meter readings for 24 land zones made available for a 12 month selection period. The process involved 840 960 water meter records that were reviewed, in order to identify the selected case study sites.

Subsequent to the execution of the Zednet system, a data record catalogue comprising regular intervals of 15 minute flow rates (m^3/h) was aggregated. A categorisation, selection and verification process was performed so as to successfully derive a set of just and feasible parameter inputs. Since individual consumer meter readings were unobtainable, a dataset comprising bulk meter recordings were attained. Prior the completion of the above mentioned criteria, 24 land zones were made available for analyses.

In order to preserve the integrity of the research, denoted in Table 4-1, was applied when sourcing and categorizing the data records:

1. Data records had to be recorded within the Western Cape – the scope of the research was limited to the Western Cape and therefore all flow rate recordings falling outside the Province were omitted. Following the initial first step, 20 land zones were located within the Western Cape whereas 4 were not.

2. Data records had to be of extended historical length – a dataset length remains one of the key factors regarding the accuracy in the approximation of water loss. By ensuring data analyses are performed on meters with adequate record lengths, corresponding results encompass a more statistically sound confidence level. A one year record length was ultimately deemed suffice. Upon investigation, 16 land zones comprised record lengths extending further than one year whilst 8 fell short.

3. Data records had to be sourced from GCs – GC consumers fall within a higher income bracket which has an effect on maintenance affordability, type and age of water-using appliances, the ability to detect and repair leaks within the household as well as the awareness and level of care of the residents (Trow and Farley, 2004). Additionally, the size in area needed to be controlled is smaller in comparison to municipalities as GCs' infrastructures are well maintained and self-managed. In completion of phase 1, 13 land zones were not categorized as the specified land zone and were omitted. Three stands remained.

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Table 4-1: Categorisation Process (Phase 1)

Stand Number	Western Cape	Adequate Record Length	Gated Community (GC)
1	NO	YES	NO
2	YES	YES	YES
3	YES	YES	NO
4	NO	NO	NO
5	YES	YES	YES
6	YES	YES	NO
7	YES	YES	NO
8	YES	YES	NO
9	NO	NO	NO
10	YES	YES	YES
20	YES	YES	NO
21	YES	YES	NO
22	YES	YES	NO
23	YES	YES	NO
24	YES	YES	NO
TOTAL	20	16	3

Three GCs, denoted as A, B and C, successfully passed phase 1 and were deemed suitable for the research. Flow rates were collected at regular intervals of 15 minutes between 1 October 2018 and 30 September 2019 in which 34 944 flow rate recordings were yielded from each GC. The complete table following the categorisation process can be found in Appendix A.3.

Following the completion of the categorisation process, a selection model was formulated to disregard certain days with significant missing flow records so as not to jeopardise the accuracy of the workings for the research. As previously stated in the scope, the research negates the necessity of predicting or expanding data records. An extract in Table 4-2 illustrates the raw dataset in connection to the three selected distribution systems.

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Table 4-2: Raw Dataset

				A		B		C	
DATE			TIME	FLOW					
Year	Month	Day	hr:min:sec	m^3/h	L/s	m^3/h	L/s	m^3/h	L/s
2018	10	1	00:00:00	0.32	0.09	0	0	0.8	0.22
2018	10	1	00:15:00	0.24	0.07	0.4	0.11	0.4	0.11
2018	10	1	00:30:00	0.2	0.06	0.4	0.11	0.16	0.04
2018	10	1	00:45:00	0.2	0.06	0	0.00	0	0.00
2018	10	1	01:00:00	0.28	0.08	0.4	0.11	0.16	0.04
2018	10	1	01:15:00	0.24	0.07	0	0.00	0	0.00
2018	10	1	01:30:00	0.2	0.06	0.4	0.11	0.16	0.04
2018	10	1	01:45:00	0.2	0.06	0	0.00	0	0.00
2018	10	1	02:00:00	0.2	0.06	0	0.00	0	0.00
2018	10	1	02:15:00	0.2	0.06	1.2	0.33	0.2	0.06
2018	10	1	02:30:00	0.16	0.04	0	0.00	0	0.00
2018	10	1	02:45:00	0.24	0.07	0.4	0.11	0	0.00
2018	10	1	03:00:00	0.2	0.06	0	0.00	0	0.00
2018	10	1	03:15:00	0.2	0.06	0.4	0.11	0.2	0.06
2018	10	1	03:30:00	0.2	0.06	0	0.00	0	0.00
2018	10	1	03:45:00	0.24	0.07	0	0.00	0.16	0.04
2018	10	1	04:00:00	0.28	0.08	0.4	0.11	0	0.00

A no-flow recording from a GC, comprising multiple units, was considered highly unlikely and flagged for further investigation. Although the bulk meter may register a no-flow reading, cases may arise where smaller flows are not strong enough to be registered by the larger bulk meters (Courvelis and Van Zyl, 2015).

A selection model, denoted as phase 2, was formulated to locate a specific number of consecutive no-flow readings throughout a single day and exclude the entire day from the database should it not satisfy a preconditioned requirement. An excerpt of the model can be found in Appendix A.4. The model was tested for each GC in which the extent of missing data, ranging from 15 minutes to 2 hours, was analysed. Days comprising missing/consecutive no-flow readings of more than an hour were then ultimately omitted from the dataset, following the analysis of results presented in Table 4-3. Table 4-3 summarizes the results in accordance to the selection model and highlights the number of usable days along with the percentage of data filtered out for each specified distribution system. However, flow rates recorded within the MNF period (02:00 – 04:00) were not considered during the process of phase 2 as flow readings were minimal.

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Table 4-3: Selection Model Summary

Gaps Allowed		Number of Days Available		
		A	B	C
1	(15 min)	246	160	270
2	(30 min)	249	304	319
3	(45 min)	252	354	331
4	(1 hour)	254	361	337
5	(1 hour 15 min)	255	364	339
6	(1 hour 30 min)	257	364	339
7	(1 hour 45 min)	258	364	340
8	(2 hour)	260	364	342
Gaps Allowed		Data Filtered Out (%)		
		A	B	C
1	(15 min)	32.60	56.16	26.03
2	(30 min)	31.78	16.71	12.60
3	(45 min)	30.96	3.01	9.32
4	(1 hour)	30.41	1.10	7.67
5	(1 hour 15 min)	30.14	0.27	7.12
6	(1 hour 30 min)	29.59	0.27	7.12
7	(1 hour 45 min)	29.32	0.27	6.85
8	(2 hour)	28.77	0.27	6.30

The completion of the categorization (phase 1) and selection (phase 2) procedures resulted in an updated and consolidated database for the three selected water networks corresponding to three GCs. Table 4-4 presents an extract relevant to the updated databases in which the 15 minute flow rates for GCs A, B and C was collected. Shown within Table 4-4 is; the maximum recorded flow rate, the number of usable days and the updated flow rates with associated dates and times. In summation, GC A’s dataset consisted as having 254 usable days with 24384 flow rate recordings. GC B’s dataset comprised 34656 flow rate recordings with 361 days available. Lastly, GC C’s dataset included 337 days comprising 32352 flow rate recordings.

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Table 4-4: Updated Database

Max =	4.06	L/s	Days =	254	Max =	2.78	L/s	Days =	361	Max =	3.16	L/s	Days =	337
A					B					C				
DATE			TIME	FLOW	DATE			TIME	FLOW	DATE			TIME	FLOW
Year	Month	Day	hr:min:sec	L/s	Year	Month	Day	hr:min:sec	L/s	Year	Month	Day	hr:min:sec	L/s
2018	10	1	00:00:00	0.09	2018	10	1	00:00:00	0.00	2018	10	1	00:00:00	0.22
2018	10	1	00:15:00	0.07	2018	10	1	00:15:00	0.11	2018	10	1	00:15:00	0.11
2018	10	1	00:30:00	0.06	2018	10	1	00:30:00	0.11	2018	10	1	00:30:00	0.04
2018	10	1	00:45:00	0.06	2018	10	1	00:45:00	0.00	2018	10	1	00:45:00	0.00
2018	10	1	01:00:00	0.08	2018	10	1	01:00:00	0.11	2018	10	1	01:00:00	0.04
2018	10	1	01:15:00	0.07	2018	10	1	01:15:00	0.00	2018	10	1	01:15:00	0.00
2018	10	1	01:30:00	0.06	2018	10	1	01:30:00	0.11	2018	10	1	01:30:00	0.04
2018	10	1	01:45:00	0.06	2018	10	1	01:45:00	0.00	2018	10	1	01:45:00	0.00
2018	10	1	02:00:00	0.06	2018	10	1	02:00:00	0.00	2018	10	1	02:00:00	0.00
2018	10	1	02:15:00	0.06	2018	10	1	02:15:00	0.33	2018	10	1	02:15:00	0.06
2018	10	1	02:30:00	0.04	2018	10	1	02:30:00	0.00	2018	10	1	02:30:00	0.00
2018	10	1	02:45:00	0.07	2018	10	1	02:45:00	0.11	2018	10	1	02:45:00	0.00
2018	10	1	03:00:00	0.06	2018	10	1	03:00:00	0.00	2018	10	1	03:00:00	0.00
2018	10	1	03:15:00	0.06	2018	10	1	03:15:00	0.11	2018	10	1	03:15:00	0.06
2018	10	1	03:30:00	0.06	2018	10	1	03:30:00	0.00	2018	10	1	03:30:00	0.00
2018	10	1	03:45:00	0.07	2018	10	1	03:45:00	0.00	2018	10	1	03:45:00	0.04
2018	10	1	04:00:00	0.08	2018	10	1	04:00:00	0.11	2018	10	1	04:00:00	0.00
2018	10	1	04:15:00	0.10	2018	10	1	04:15:00	0.00	2018	10	1	04:15:00	0.04
2018	10	1	04:30:00	0.09	2018	10	1	04:30:00	0.11	2018	10	1	04:30:00	0.04
2018	10	1	04:45:00	0.11	2018	10	1	04:45:00	0.11	2018	10	1	04:45:00	0.11
2018	10	1	05:00:00	0.11	2018	10	1	05:00:00	0.11	2018	10	1	05:00:00	0.00

4.2 Data Verification

In order to validate the feasibility and practicality of the dataset used for the research, checks were performed and correlated with calculations based on the guidelines stipulated in CSIR (2019) along with previously published case studies. The addition of grey-water reuse, rainwater harvesting, borehole instalments and heightened public awareness has led to a relatively substantial drop in water consumption levels (Parks *et al.*, 2019 and Sousa *et al.*, 2018). As a result, the aforementioned factors should be taken into consideration whilst analysing and evaluating the viability of the data when comparing readings to standardised guidelines and the workings of previous studies.

Shown in Table 4-5 is the procedure followed in calculating the estimated peak flows for all three GCs according to the recommended guidelines stated in CSIR (2019). The following GC-specific data had to be obtained prior the application of Equation 4-1:

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1. The total number of units occupied – since the AADD was measured in kL/unit/d, the total number of households located within the GC was required. The summations of households were attained through the identification of plots situated on each GC site plan - confidentiality prohibits the disclosure of drawings. Note, the component ‘N’ used in Equation 4-1 represents the total number of units occupied during the time the research was undertaken as not all plots were being used. Various units were either still under construction, had been purchased as holiday homes or had not yet been sold.

2. The average plot area – in order to identify which specific class, in terms of the AADD bracket, applied to each GC, average plot areas had to be determined. The estimation was achieved by measuring the plot sizes using Google Earth in addition to sourcing plot areas from a number of property advertisements - approximations are presented in Appendix A.5.

Table 4-5: Peak flow calculations based on CSIR (2019) criteria

GC	Total number of units	Units occupied during Study	Average plot area (m^2)	Land use
A	145	122	720	Residential Estate
B	371	161	360	
C	87	77	8 800	
GC	AADD (L/day) - (CSIR, 2019)	AADD (L/s)	PF (CSIR, 2019)	Peak flow (L/s)
A	800	0.009	3.6	4.1
	1000	0.012		5.1
B	500	0.006	3.6	3.4
	600	0.007		4.0
C	1300	0.015	3.6	4.2
	2000	0.023		6.4

Table 4-6 presents the correlations between the peak flow calculations, based on the CSIR (2019) criteria, and the highest recorded flow rates measured at all three distribution systems. Although the actual peak flows were lower in comparison, it was to be expected for reasons previously mentioned. Furthermore, the guidelines stated in CSIR (2019) are standardised and as a result do not always reflect the true representations concerning site specific scenarios. Nonetheless, an adequate level of correlation existed in validating the legitimacy of the actual peak flow rates for GCs A, B and C.

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Table 4-6: Summation of peak flow comparisons

	Peak flow (L/s)	
Gated Community	CSIR (2019)	Actual recordings
A	4.6	4.1
B	3.7	2.8
C	5.3	3.2

The initial stage of the verification process compared the actual peak flows to calculations based on the CSIR (2019) criteria, for which an acceptable range in variability was found. The second stage was centred on the correlation of the actual AADD/Plot size for the research and the findings of the case study conducted by Du Plessis and Jacobs (2018). The actual AADD for GCs A, B and C was calculated by determining the average of all daily consumptions throughout the specified year for which an extract of the procedure can be found in Appendix A.6. Note, only days that passed phase 2, the selection process, were used in the calculation of the AADD. The preferred units, L/s, were converted to kL/Plot/d so as to correlate with the workings of the Du Plessis and Jacobs (2018) study. Furthermore, the number of plots equated to the number of households occupied during the research.

Figure 4-2 illustrates the comparisons between the previously published case study, discussed in Section 2.4, and the data sourced from GCs A and B. The average plot sizes were previously obtained during the initial stage of the verification process. Since the plots located within GC C were significantly larger in size, approximately 8800 m^2, GC C did not fall within the range and so, is not presented in Figure 4-2.

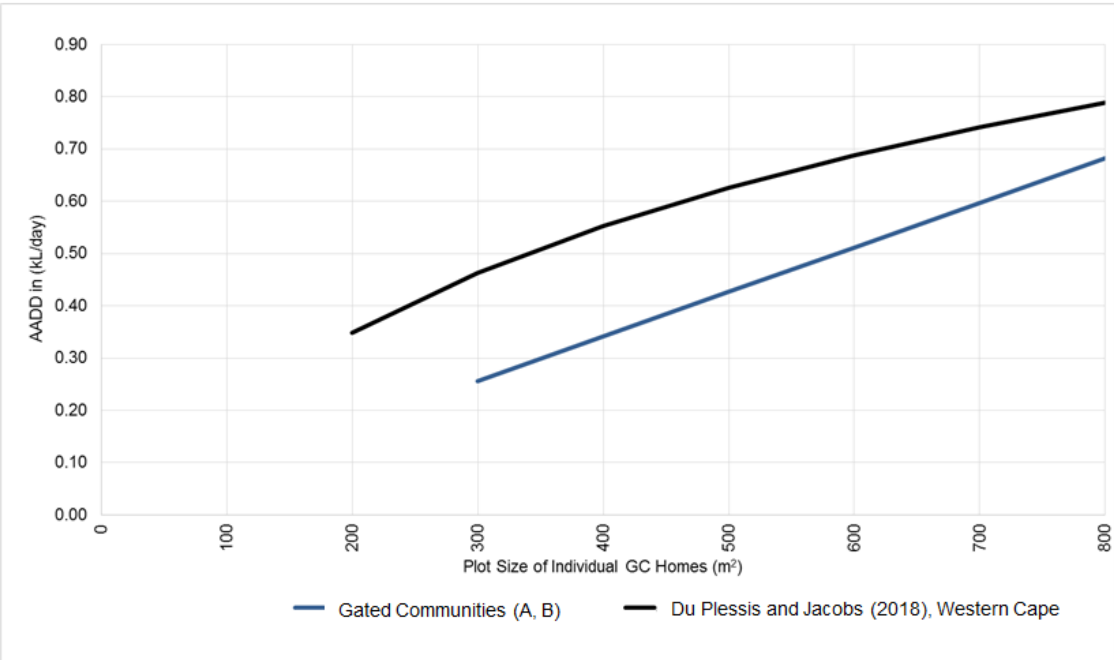

Figure 4-2: Former case study comparisons

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Figure 2-7 was simplified on the basis that the datasets for GCs A, B and C be related with the workings of the Du Plessis and Jacobs (2018) case study, focusing specifically on the Western Cape region (regression C line in Figure 2-7). The former study comprised 1402 GCs, located within the stated Province, having an average plot size of 323 m^2 whilst the research comprised 3 GCs averaging plot sizes that ranged from 360 m^2 to 8800 m^2. Despite the fact that the AADD values relevant to the study were to some extent lower in comparison, causes for this take account of the aforementioned dissimilarities between the studies along with the period of time in which the records were obtained. The Du Plessis and Jacobs (2018) data catalogue consisted of flow rates collected from November 2012 to September 2014 and thus, preceded the 2017 Day-Zero drought and all the aberrations that followed.

The “Day Zero” crisis in the Western Cape in 2017 has raised water scarcity awareness, targeting water demand management strategies aimed at the prevention of waste, misuse and overuse of water resources while encouraging conservation. The reality of zero water reserves has had a significant impact on most of those South Africans who experienced extremities of the situation. A number of studies have been undertaken to investigate the effect of alternative solutions viz. desalination plants, dual reticulation, water reuse and water efficient appliances (Gurung et al., 2015) in most water stressed countries.

The 2017 Cape Town water crisis in South Africa was a period of severe water shortage which saw the water levels of six major dams supplying the City, which relies almost entirely on rainfall, approach 13.5 percent. This would have potentially made the City of Cape Town the first major city in the world to run out of water whilst experiencing adversities concerning its economy, agriculture, tourism, hydrological poverty, public health and fire risks. In a bid to curb water usage, several significant water restrictions were implemented by the Department of Water and Sanitation (DWS) and thus able to reduce its daily water consumption by more than half and as a result, continually postpone its estimate for “Day Zero”. These mitigation strategies comprised supply augmentation, urban water demand management, enforced reductions, hikes in water tariffs, alternative water supply, water-efficient farming and educational water-saving campaigns (Burls et al., 2019). Although the Western Cape were able to recover from a drought that was found to have a severity to statistically occur approximately once every 300 years (Lin, 2019), the need for the improvement in water demand management remains a concern.

In the aftermath of these severe water shortages and with the addition of grey-water reuse, rainwater harvesting, borehole instalments and a general rise in the public’s water wise approach, Cape Town’s daily water consumption has risen to some extent but not to levels before the crisis.

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Whilst the flow rates recorded at GCs A, B and C were slightly lower than the calculations based on the guidelines stipulated in the CSIR (2019) criteria as well as the findings in the Du Plessis and Jacobs (2018) case study, justifiable explanations were drawn. The consolidated record catalogues comprised of flow rates that compared relatively well with the results of Du Plessis and Jacobs (2018).

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5. Analysis/Results

The chapter presents the results following the implementation of the methodology described in Chapter 4 for GCs A, B and C. The procedure followed in the determination of the initial night flow recordings to the approximation of the ILI ratios is presented in its entirety. The chapter focuses exclusively on the results as discussions in analysing the findings are addressed in succeeding chapters. Furthermore, due to the length of flow records, the research is aided through the illustration of excerpts sourced from the complete dataset tables.

5.1 Night Flow Register

The general layout of a GC water distribution system is illustrated in Figure 5-1. Each GC comprised a number of residential plots in a single, discreet, water distribution zone. Each GC contains numerous individual consumer meters connected to the distribution system. The water was delivered via the mains and linked to the municipal pipeline through the bulk water meter. The database comprised an aggregated 105 120 flow rates recorded amongst 360 households for GCs A, B and C.

The water use analysed in the research would thus include:

(i) The legitimate consumption of all the individual GC consumers,
(ii) Water leakage and losses in plumbing systems of all consumers,
(iii) Water use by the GC for common purposes, and
(iv) Water leakage and losses in the GC water distribution system.

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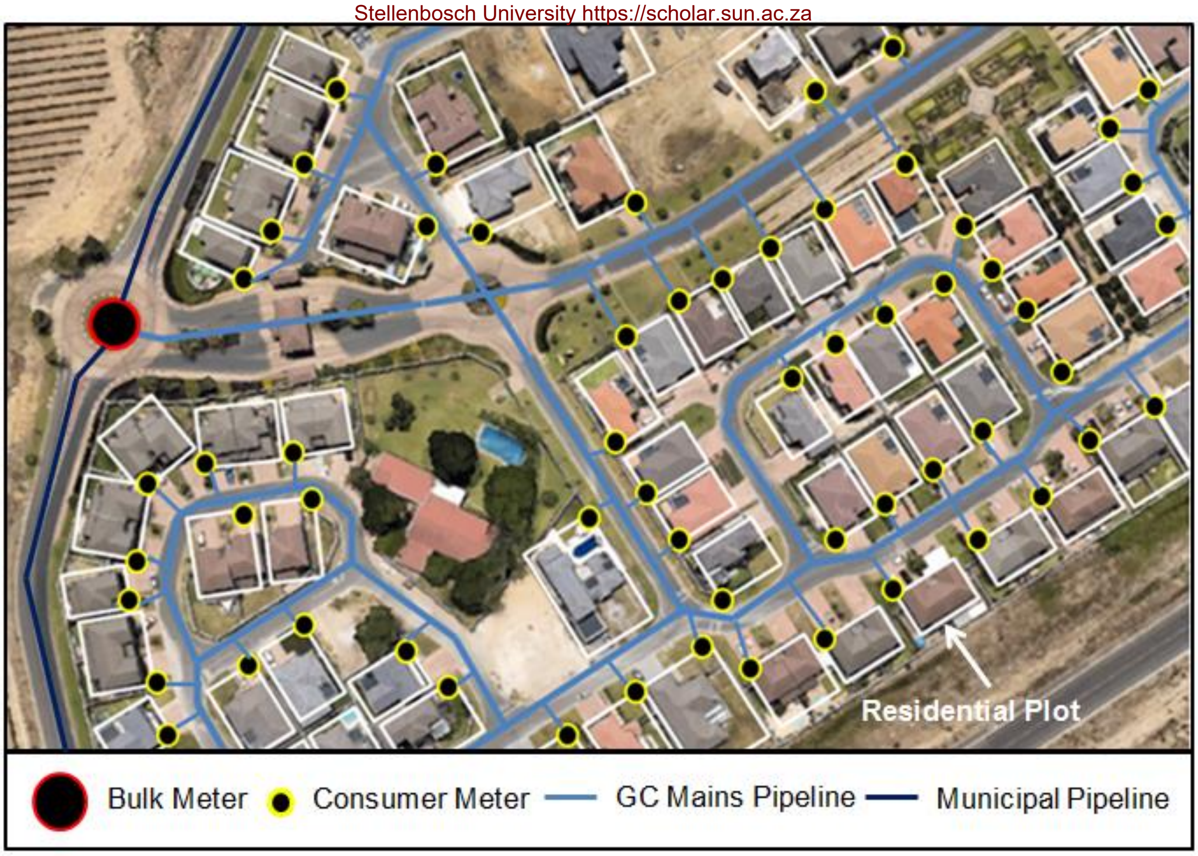

Figure 5-1: Typical GC layout

Figure 5-2 depicts a single day, 2 October 2018, for which the 15 minute flow rates for GC A were recorded. For the duration of the time frame, while consumption levels continued to fall, leakage was at a maximum proportion of the total flow, as previously stated in Figure 2-5.

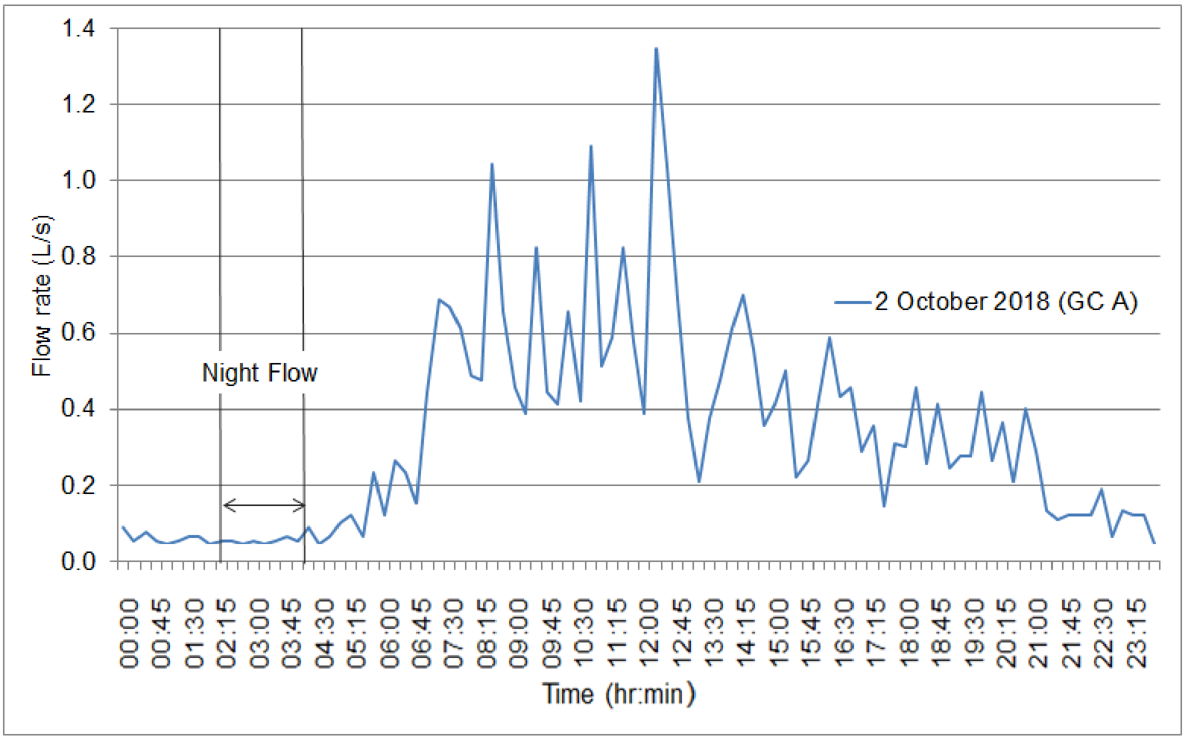

Figure 5-2: Daily flow readings for GC A

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An extract taken from the model formulated to determine the night flow register for GC A is presented in Table 5-1. The 15 minute flow rates falling within the specified night flow period (2 – 4 am) were extracted and further consolidated. The process was repeated for GCs B and C to form a database catalogue consisting night flows needed in the determination of the MNF as discussed in sections to follow. The night flows for the three selected GCs were ranked and plotted on a non-exceedance probability curve as illustrated in Figure 5-3.

Table 5-1: Night flow database for GC A

A							
DATE			TIME	FLOW	NIGHT FLOW	CONSOLIDATED NIGHT FLOW	MNF
Year	Month	Day	hr:min:sec	L/s	L/s	L/s	L/s
2018	10	1	00:00:00	0.09		0.06	
2018	10	1	00:15:00	0.07		0.06	
2018	10	1	00:30:00	0.06		0.04	
2018	10	1	00:45:00	0.06		0.07	
2018	10	1	01:00:00	0.08		0.06	0.06
2018	10	1	01:15:00	0.07		0.06	
2018	10	1	01:30:00	0.06		0.06	
2018	10	1	01:45:00	0.06		0.07	
2018	10	1	02:00:00	0.06	0.06	0.08	
2018	10	1	02:15:00	0.06	0.06	0.04	
2018	10	1	02:30:00	0.04	0.04	0.06	
2018	10	1	02:45:00	0.07	0.07	0.06	
2018	10	1	03:00:00	0.06	0.06	0.04	
2018	10	1	03:15:00	0.06	0.06	0.06	0.05
2018	10	1	03:30:00	0.06	0.06	0.04	
2018	10	1	03:45:00	0.07	0.07	0.06	
2018	10	1	04:00:00	0.08	0.08	0.07	
2018	10	1	04:15:00	0.10		0.06	
2018	10	1	04:30:00	0.09		0.06	
2018	10	1	04:45:00	0.11		0.06	
2018	10	1	05:00:00	0.11		0.06	
2018	10	1	05:15:00	0.07		0.04	
2018	10	1	05:30:00	0.13		0.07	0.05
2018	10	1	05:45:00	0.26		0.06	
2018	10	1	06:00:00	0.09		0.08	
2018	10	1	06:15:00	0.22		0.09	
2018	10	1	06:30:00	0.29		0.06	

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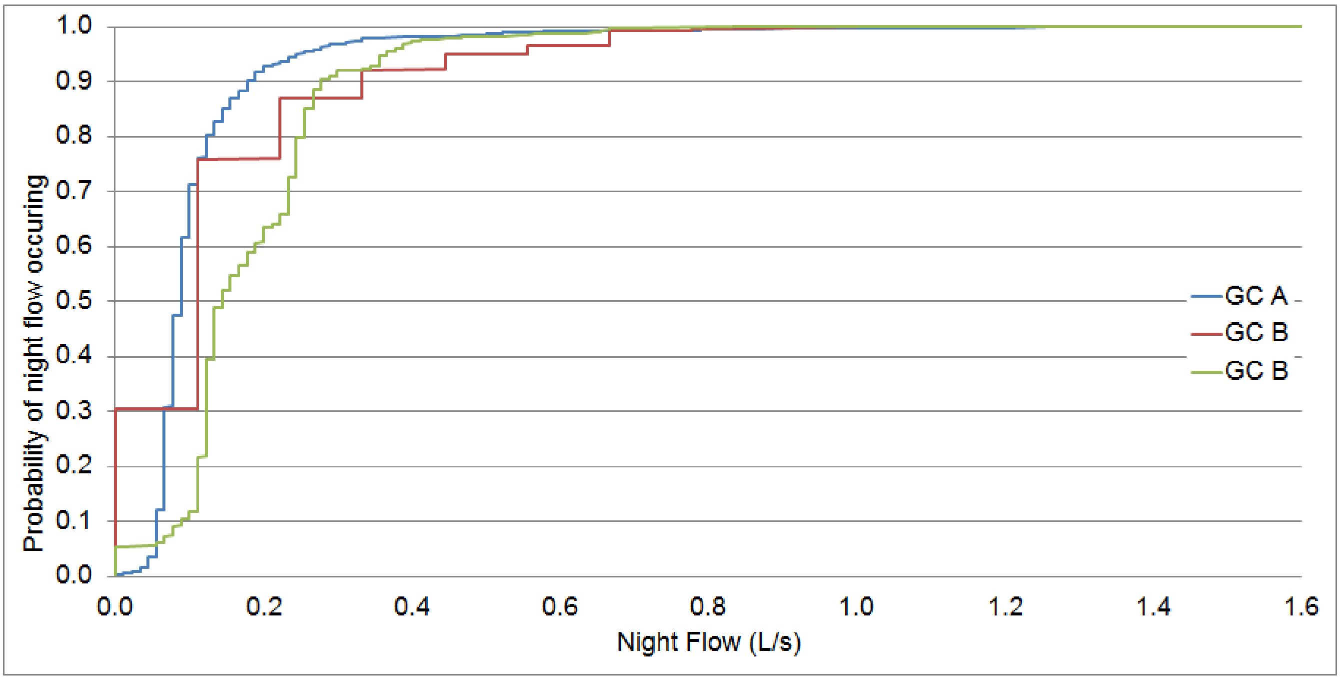

Figure 5-3: Non-exceedance probability curve of collective GC night flows

Values representative of the average night flows for GCs A, B and C is shown in Table 5-2. The average household night flows per GC were calculated by dividing the total GC night flow rate by the number of units per GC. Note the result over estimates the MNF per property, as the bulk water meter data used for the analysis would include some legitimate common water use on the GC property and also water leakage and loss in the GC distribution system. The MNF values per household cannot be compared directly to values for MNF per home in other studies. However, this provides a useful means to crudely compare the MNF magnitude in the study area to earlier reported values per home.

Table 5-2: Average GC night flows

Gated Community	A	B	C	Units
Average Night Flow	0.11	0.14	0.18	L/s
Average Household Night Flow	79.48	74.46	204.49	L/con/d

5.2 Minimum Night Flow

The MNF comprised the lowest consecutive flow rates for the duration of one hour and was sourced from the night flow period. Figure 5-4 further illustrates the MNF period for the same day as depicted in Figure 5-2. In addition, the implementation of the model formulated in Table 5-1 aided in obtaining the MNF values from the night flow register for GCs A, B and C.

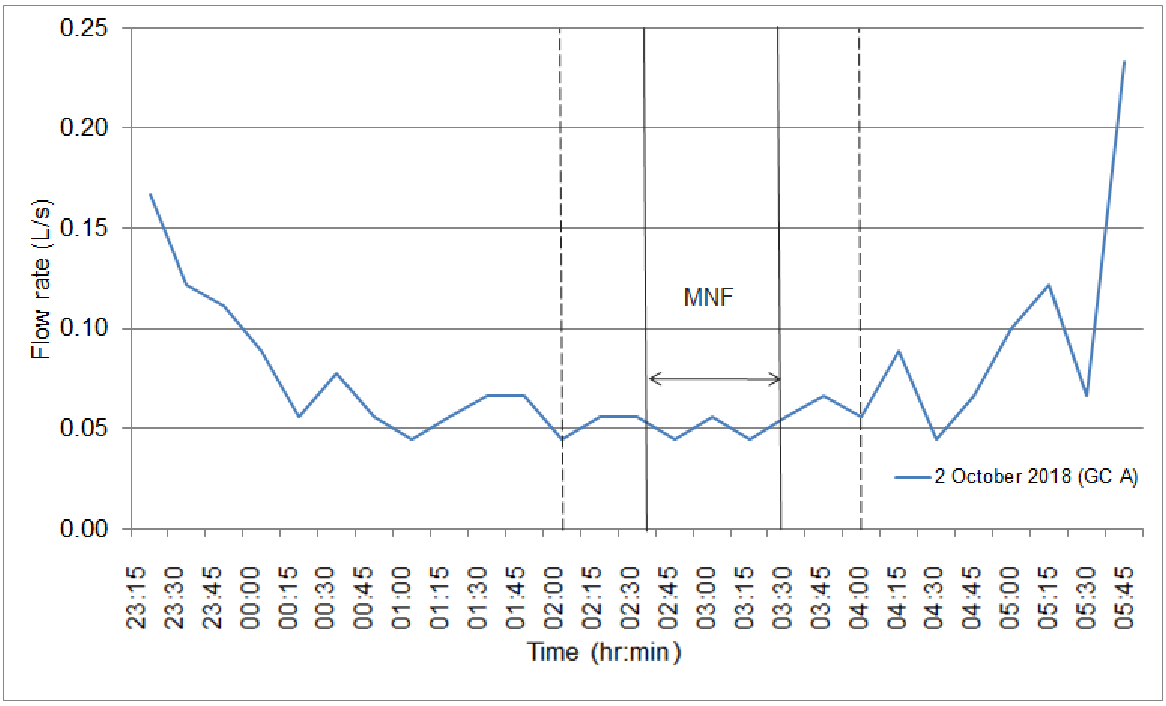

Figure 5-4: Daily MNF period for GC A

Section 4.1 stated that a no-flow recording from a GC bulk meter, comprising multiple households, was relatively improbable and flagged for further investigation. A more stringent filter was applied to the MNF database in which the placements of no-flow recordings were identified in relation to previously omitted days. Table 5-3 indicates the location of the aforementioned flows in relation to the daily MNF recordings. Throughout the specified time frame, the majority of flagged readings fell adjacent to days failing the initial criterion and highlighted brief periods where the accuracy in recordings were potentially jeopardized and thus, removed from the dataset.

Table 5-3: No/suspiciously low flows for GC A

Gated Community A				
DATE			MNF	SUSPISCIOUS FLOWS
Year	Month	Day	L/s	X
2018	10	6	0.058	
2018	10	7	0.053	
2018	10	8	0.050	
2018	10	9	0.050	
2018	10	10	FAILED	
2018	10	11	FAILED	
2018	10	12	0.000	X
2018	10	13	0.000	X
2018	10	14	0.000	X
2018	10	15	FAILED	
2018	10	16	FAILED	
2018	10	17	0.000	X
2018	10	18	FAILED	
2018	10	19	0.006	X
2018	10	20	0.011	X
2018	10	21	0.000	X
2018	10	22	0.067	
2018	10	23	0.064	
2018	10	24	0.067	

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The MNF relative to the three GCs were ranked and plotted on a non-exceedance probability curve presented in Figure 5-5. Note, the night flow period was defined between the hours of 2 and 4 am from which the MNF for one hour was sourced. Furthermore, Table 5-4 summates the approximation of the average MNF values for GCs A, B and C in addition to the estimated household MNF per GC.

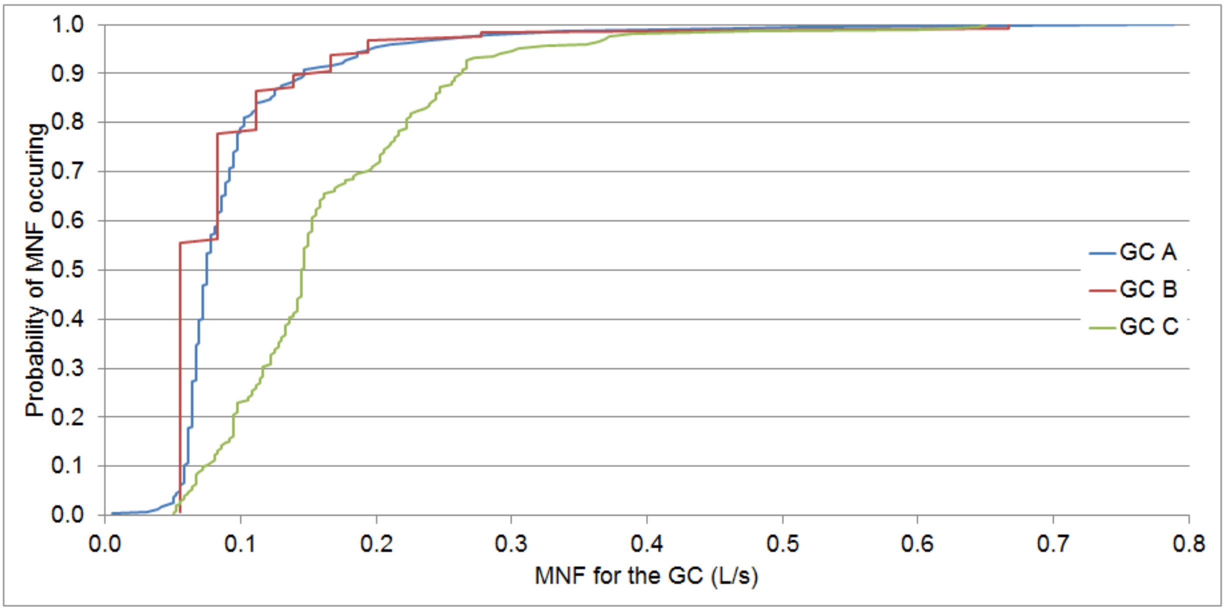

Figure 5-5: Non-exceedance probability curve of collective GC MNF flows

Table 5-4: Average GC MNF

Gated Community	A	B	C	Units
Average MNF	0.10	0.09	0.17	L/s
Daily average Household MNF *	68.02	48.98	186.55	L/con/d

* Assuming constant MNF throughout the day

Note the MNF sourced from the night flow period is relatively higher at night and would not be constant throughout the day. During night consumption, whilst flow rates are considered minimal, a resultant upsurge in pressures exists subsequent the highest ratio of MNF to actual usage.

5.3 Unavoidable Annual Real Losses

The determination of the UARL provides a quantifiable measurement representative of the lowest achievable volume for a particular distribution system in good condition. In applying system-specific parameters to Equation 2-1, UARL values were obtained for GCs A, B and C. Presented in Table 5-5 are the parameters used in quantifying the UARL per GC. The parameters involved are: the number of connections (Nc), the length of the mains pipeline

(Lm), the length of the private service pipeline (Lp) and the average operating pressure (AOP).

Table 5-5: UARL Input Parameters

	A	B	C	Units
Nc	122	161	77	con
Lm	2.57	1.80	4.07	km
Lp	0.00	0.00	3.08	km
AOP	30			m
	40			m
	50			m

The water pipe network topologies for the three GCs were not available at the time of research. Some parameter values, including the mains pipe length and the length of service connections, were unobtainable. The mains pipe length was estimated by considering the length of the roads in each GC. In measuring the distance of the roads running adjacent to the residential plots within each specified GC, the length of the mains pipeline (Lm) was recorded. Figure 5-6 illustrates the procedure followed for the approximation of the abovementioned input parameter for GC B. In cases where households were accessible by means of multiple roads, the length of Lm was included once as each residential unit was fed by a single distribution pipeline.

Figure 5-6: Calculating Lm for GC B

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Section 2.3.1 stated that in most urban developments, individual consumer meters are located at the property boundary and thus, nullifies the length of the private service pipeline (Lp). Due to the average plot sizes, GCs A and B were denoted as applying to the condition for which the Lp component was omitted from the formula. Figure 5-7 presents the typical meter layout within GC B and further illustrates the annulment of the Lp parameter. A substantially larger average plot size of approximately 8800 m^2 meant that the Lp component in GC C became a contributing factor. The summation of the distances measured between the property line and all households located within GC C resulted in the total length of the Lp for the specified distribution system. Lastly, as the AOP constantly fluctuates during the duration of a singular day for different water networks, a pressure range of 3-5 bar was deemed practical and analysed for the research.

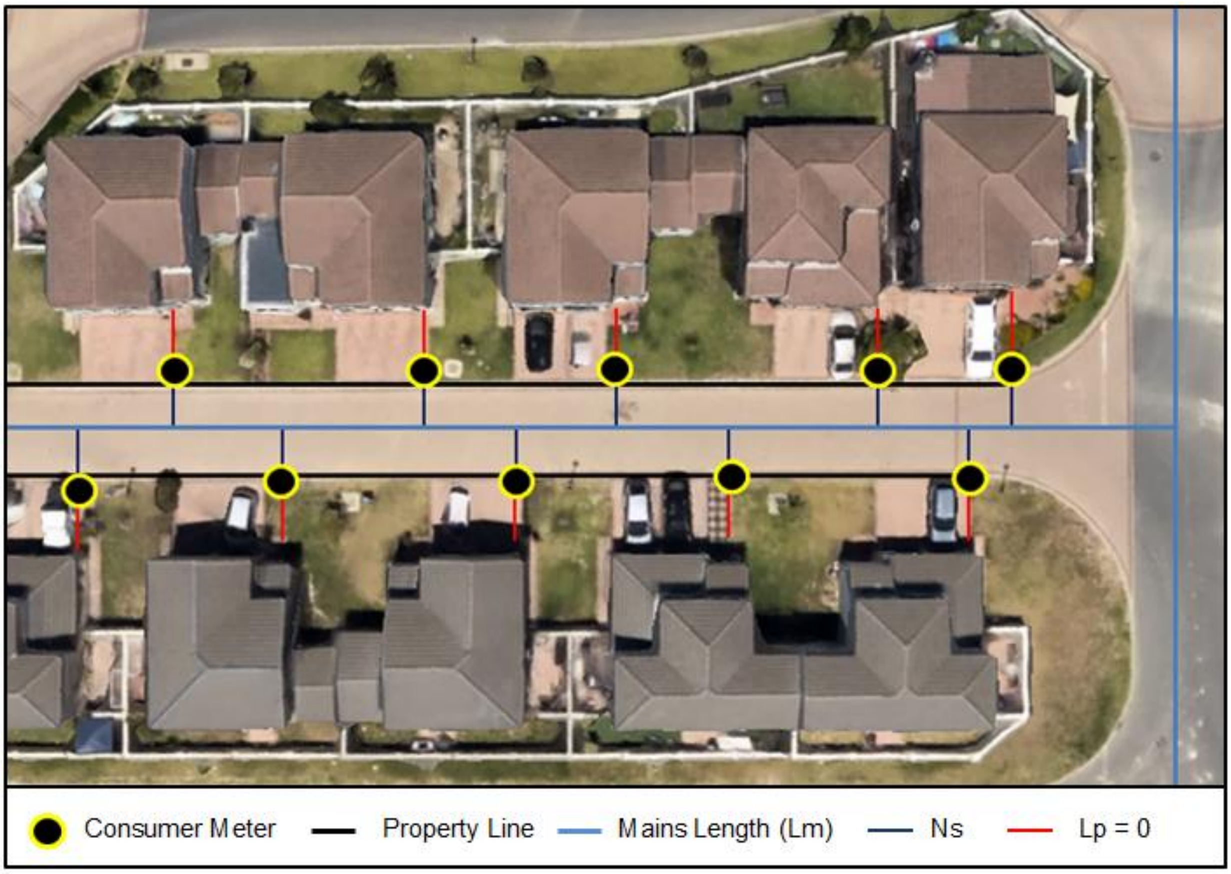

Figure 5-7: Individual meter placements for GC B

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The UARL values following the implementation of Equation 2-1 is presented in Table 5-6 for the specified distribution systems within GCs A, B and C. The findings are in accordance to the utilization of the input parameters indicated in Table 5-5 with an AOP range of 3-5 bar.

Table 5-6: UARL values for GCs A, B and C

Unavoidable annual real losses (UARL)					
Gated Community		A	B	C	Units
AOP	30 m	4.32	4.83	6.36	kL/d
	40 m	5.76	6.45	8.48	kL/d
	50 m	7.19	8.06	10.60	kL/d

5.4 Infrastructure Leakage Index

Assessing the performance of a distribution system allows for the evaluation of the current overall management in terms of leakage control purposes. The ILI, a non-dimensional performance indicator, was established by means of the implementation of Equation 2-3.

The CARL component was representative of the most viable estimate of the average real losses within the specified GCs. Equation 2-2 takes account of the LDNC as a contributing factor when approximating the CARL. With flow recordings sourced from the MNF period, when consumption levels were minimal, the LDNC component was assumed to be minor and have little to no effect and consequently omitted. The CARL was measured from the MNF period and proportioned to the UARL values presented in Table 5-6 for current operating pressures and continuity of supply. Table 5-7 displays an excerpt of values representative of the components established in the water balance for GC A. Table 5-7 presents the MNF, CARL, UARL and ILI for all days having met the criteria process, for the three assumed values of AOP.

Table 5-7: Extract of ILI for GC A

Gated Community A					AOP		
					30 m	40 m	50 m
					UARL (L/d)		
DATE			MNF	CARL	4317	5756	7195
Year	Month	Day	L/s	L/d	ILI		
2018	10	1	0.06	4800	1.11	0.83	0.67
2018	10	2	0.05	4320	1.00	0.75	0.60
2018	10	3	0.05	4560	1.06	0.79	0.63
2018	10	4	0.05	4320	1.00	0.75	0.60
2018	10	5	0.06	5520	1.28	0.96	0.77
2018	10	6	0.06	5040	1.17	0.88	0.70
2018	10	7	0.05	4560	1.06	0.79	0.63
2018	10	8	0.05	4320	1.00	0.75	0.60
2018	10	9	0.05	4320	1.00	0.75	0.60
2018	10	22	0.07	5760	1.33	1.00	0.80
2018	10	23	0.06	5520	1.28	0.96	0.77
2018	10	24	0.07	5760	1.33	1.00	0.80
2018	10	25	0.07	5760	1.33	1.00	0.80
2018	10	26	0.06	5280	1.22	0.92	0.73
2018	10	27	0.06	5520	1.28	0.96	0.77

A graphical representation of the ranked ILI ratios in connection to the specified distribution systems is plotted in Figure 5-8, for an AOP of 30 m. Comparative results presenting the findings associated to operating pressures 40 and 50 m can be found in Appendix A.7.

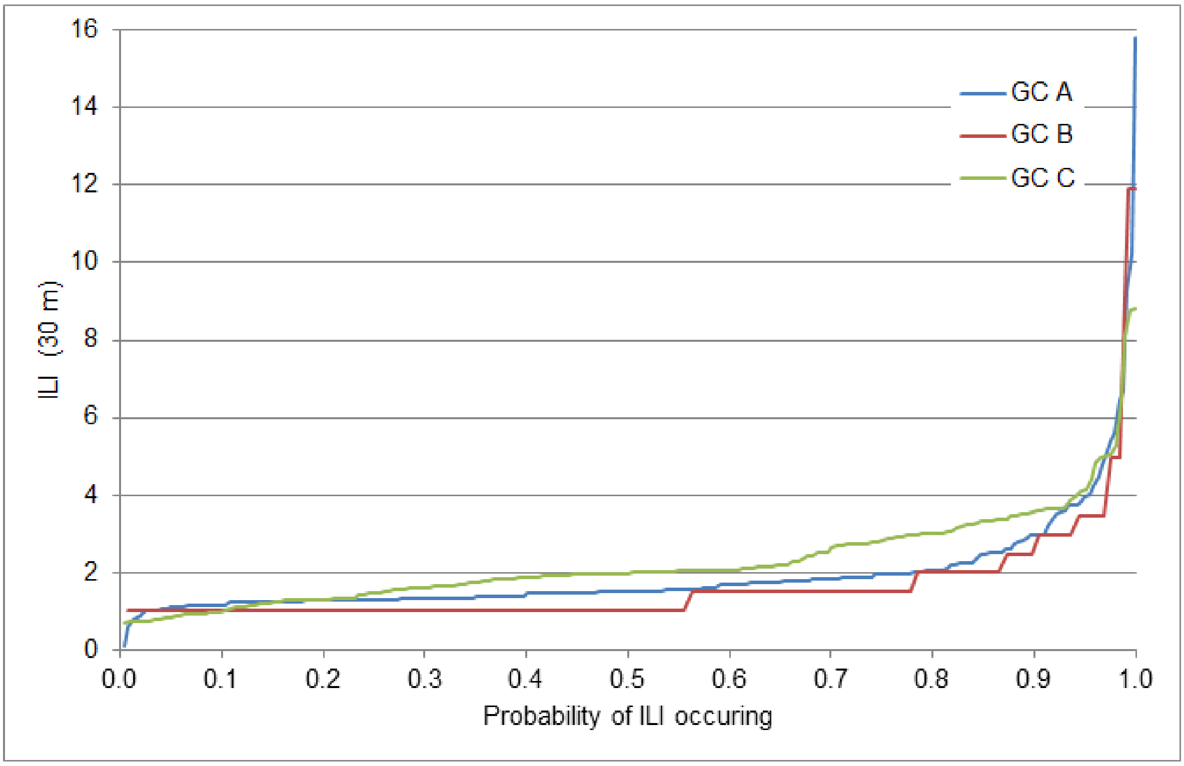

Figure 5-8: Non-exceedance probability of ILI for an AOP of 30 m

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Furthermore, Figure 5-9 correlates the ILI workings with respect to GC A for the chosen range of AOP. The process was followed for GCs B and C and displayed in Appendix A.8.

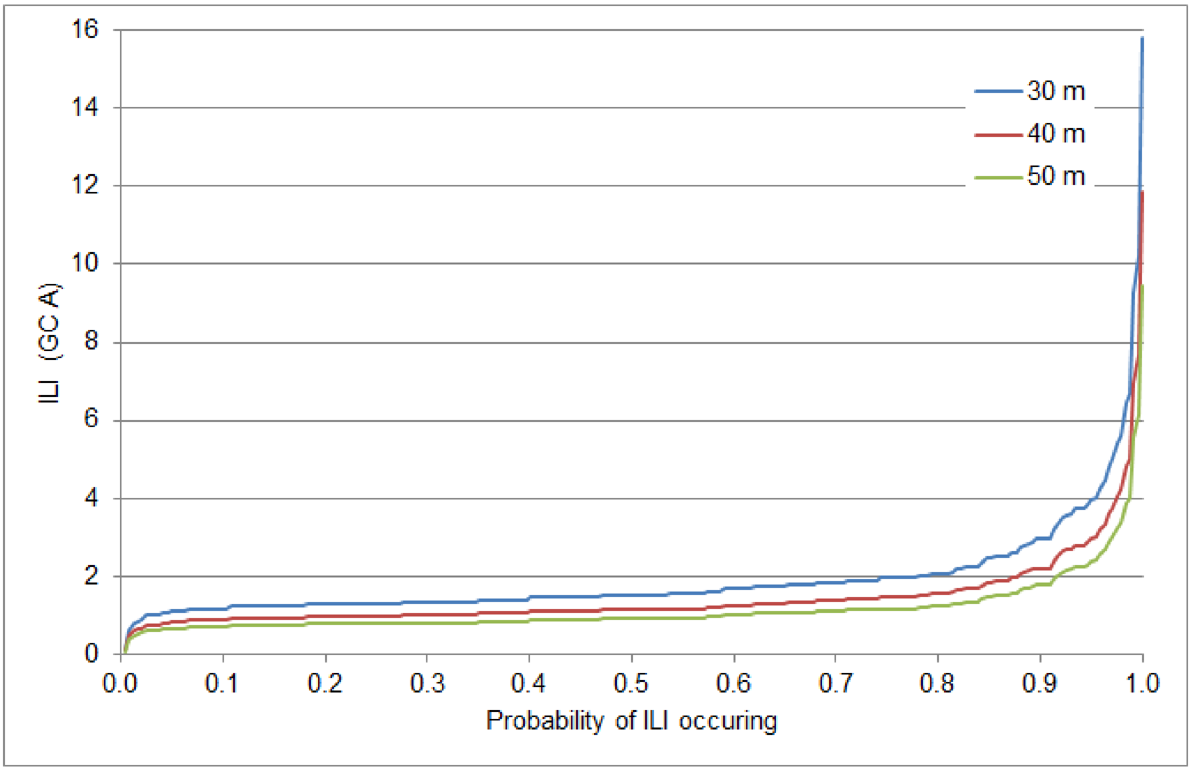

Figure 5-9: Non-exceedance probability curve for ILI for GC A

The average ILI for the specified distribution systems are presented in Table 5-8 for operating pressures of 30 m, 40 m and 50 m. The ILI is an indication of leakage detection and repair performance, with lower values suggesting better performance.

Table 5-8: Summation of ILI for GCs A, B and C

Infrastructure Leakage Index (ILI)				
Gated Community		A	B	C
AOP	30 m	1.92	1.63	2.26
	40 m	1.44	1.22	1.69
	50 m	1.15	0.98	1.36

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6. Discussion

The research investigated the extent of real losses from drinking water networks operated by GCs. The concept was to analyse the flow rate datasets pertinent to the selected distribution systems so as to segregate the components of real loss within the night flow register. This chapter addresses the findings of the research and compares the workings with prior research.

6.1 Current annual real losses

ESRI, an international supplier of geographic information system software, provides national statistics via GIS and geo-database management applications. According to ESRI (2020) stipulated that the average household size in South Africa during the time of research was approximately 3.3 people per household. Presented in table 6-1 are the comparative values in accordance with the actual MNF recorded and the MNF approximations based on the WRC (1994) criteria.

Table 6-1: MNF values for GC A, B and C

Gated Community	A	B	C	Units
Actual Average MNF	0.10	0.09	0.17	L/s
MNF based off WRC (1994) criteria	0.22	0.30	0.14	L/s

The actual MNF values are relatively lower than the calculations based on the WRC (1994) workings. Justifiable explanations could potentially encompass the dissimilarities between normal distribution systems to those operated by GCs. Moreover, the time period between the conductions of both studies has meant advancements in water leakage control and management.

Defined in Table 6-2 are the average CARL values approximated for GCs A, B and C and in so doing, provide insight into the extent of real losses within the selected distribution systems. The implementation of Equation 2-2 revealed that GC A comprised households measuring CARL between 0.90 and 23.28 L/h with an average of 2.83 L/h. GC B dataset revealed households measuring a range between 1.24 and 14.91 L/h and an average CARL of 2.04 L/h. Finally, the analysis of GC C found households experiencing a low of 2.34 L/h and a high of 30.39 L/h averaging a CARL of approximately 7.77 L/h.

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Table 6-2: Average CARL for GCs A, B and C

Gated Community	A	B	C	Units
CARL	0.90 - 23.28	1.24 - 14.91	2.34 - 30.39	L/con/h
Average CARL	2.83	2.04	7.77	L/con/h

Studies revealed that households in the USA held measurable losses averaging 1.6 to 15.8L/h (Mayer *et al*., 1999). According to Gascón *et al,* (2004), an average rate of 17 L/h was recorded throughout Spain. A later study conducted by Arrequi *et al.* (2006), found households losing 2 to 40 L/h with certain losses approaching a high of 100 L/h. A case study specific to South Africa was performed on residential households located within Windhoek and Swakopmund. Fourie (2004) established an average rate of 20.3 L/h and 9L/h respectively.

The findings presented in Table 6-2 hold relatively close similarities in accordance with the previously published international studies. The research conducted by Fourie (2004) for South African households revealed slightly higher rates of loss in relation to the CARL component. As the research focuses exclusively on smaller self-managed and self-maintained distribution systems, comparatively lower water losses are to be expected for households within GCs.

GC C was recorded as having a noticeably higher CARL but remained within an acceptable and feasible range. Due to the time period in which flow rates were extracted and analysed, the LDNC component was assumed to be minor and consequently negated. However, GC C comprises high income homeowners with significantly larger plot sizes. Equipped with large swimming pools and the capacity to accommodate sufficient grounds for horses, a component of night time irrigation and the refilling of swimming pools becomes a plausible factor. Table 6-3 illustrates the average CARL for GC C highlighting correlations in accordance with the driest and wettest months pertinent to the specified site during the time of research. January, comprising the driest month reported the highest average CARL whilst August reporting the wettest month revealed the lowest average CARL.

Table 6-3: Rainfall vs. average CARL for GC C

Gated Community C		
Rainfall	Month	Average CARL (L/d)
Driest Month	January	26387
Wettest Month	August	10013

According to Fanner *et al.* (2015), a default LDNC value of 1.7 L/con/h was used for the majority of water utilities but is no longer considered acceptable due to variable system-specific parameters. A statistical approach was used to analyse 12004 residential households resulting in an average LDNC of 3.69 L/con/h. In practice, the process in determining the LDNC is improbable as fluctuations become apparent. Further research can investigate the LDNC component for GC C so as to implement the means in quantifying its effects.

A study undertaken in South Africa reported households experiencing 20 to 35% of water loss according to projects performed in Kagiso, Tembisa and Hermanus (McKenzie, 2002). According to Alliance to Save Energy (2006), research conducted in Munsieville in Mogale City resulted in a loss of approximately 38% of the total household consumption. Presented in Table 6-4 is the water loss expressed as a percentage of the total SIV for the three selected distribution systems. GCs A and B reported a 21% and 15% CARL respectively, a moderately lower loss percentage in contrast to prior research. GCs are held accountable for the management of infrastructure ensuing in greater meter accuracy, efficient leak detection and faster repair response times (Du Plessis and Jacobs, 2018; Knox, 2020; Lugoma *et al.*, 2011). As a result, a lower percentage of loss in a GC is to be expected.

Table 6-4: CARL percentage of SIV

Gated Community	A	B	C	Units
Average CARL	8.30	7.89	14.36	kL/d
Average SIV	40.02	51.29	27.45	kL/d
Percentage lost	20.73	15.37	52.33	%

GC C recorded a significantly higher CARL of 52% of the total SIV. The GC is considered as housing more agricultural developments than smaller individual units and in so doing, leads to higher volumes of irrigation. According to Park and Smith (2008), the most practical irrigation time is during nightfall and more precisely, before 5 am as evaporation rates and surges in water consumption are minimal. Further research investigating the LDNC for the GC can highlight a more accurate approximation of the CARL pertinent to the system. The

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implementation of the average LDNC value of 3.69 L/con/h stipulated by Fanner *et al.* (2015) would result in a decrease of the CARL from 52% to a more feasible 27%.

Lastly, a case study conducted by Seago *et al.* (2004) assessed the levels of water loss in relation to 30 utilities described in Section 2.3.2. An average CARL of 340 L/con/d was established for South Africa's distribution systems as compared to the international dataset average of 276 L/con/d. Table 6-5 illustrates the average CARL for the selected GCs.

Table 6-5: Average CARL

Gated Community	A	B	C	Units
Average CARL	68.02	48.98	186.55	L/con/d

Results revealed a substantially lower average CARL in connection to the findings of the Seago *et al.* (2004) case study. Potential justifications revert back to the time in which the study was conducted. Since 2004, advances in leak detection management have meant a steady decrease in recorded water losses. Furthermore, the utilities analysed during the research were municipally owned whereas GCs A, B and C were self-managed and self-maintained distribution systems.

6.2 The unavoidable annual real losses

The total volume of UARL is presented in Table 6-6 and in so doing, signifies the lowest achievable volume within the specified distribution systems. Due to continuous fluctuations in the AOP, a feasible pressure range of 3-5 bar was analysed in the research. In accordance to the AOP, GC A reported an average UARL range between 1.7 and 2.8m^3/km/d. GC B recorded values ranging from approximately 2.7 to 4.5 m^3/km/d whilst GC C was found to comprise averages of 0.9 to 1.5 m^3/km/d. Note, prior research suggests that the wide range in local contributing factors and limiting constraints typically restrict the application of UARL approximations to situations located outside certain regions of origin.

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Table 6-6: Average UARL values

		UARL (m^3/km/d)		
Gated Community		A	B	C
AOP	30 m	1.68	2.69	0.89
	40 m	2.24	3.59	1.18
	50 m	2.80	4.48	1.48

A study conducted in the USA reported values of UARL in the range of 2.4 to 7.1 m^3/km/d (AWWA, 1998). According to the Managing Leakage Report B (1994), Germany recorded averages ranging between 1 and 5 m^3/km/d whilst France was measured as having UARL values from 1.5 to 7 m^3/km/d (Agence, 1990). The findings presented in Table 6-6 for the selected distribution systems are were relatively similar as those presented in earlier studies.

The equation for approximating the UARL was initially established by Lambert *et al.* in 1999. The advancement in leak detection equipment and control management has questioned the legitimacy of the UARL as values are potentially out dated. Furthermore, this research dealt exclusively with small self-managed and well maintained systems for which the UARL needs to be adjusted to compare with normal distribution systems.

Seago *et al.* (2004) reported an average UARL of approximately 59.93 L/con/d for 30 utilities situated throughout South Africa. Presented in Table 6-7 is the average UARL for the specified distribution systems in connection with the chosen AOP range. Note, the units have been changed for comparative reasons.

Table 6-7: Average UARL

		UARL (L/con/d)		
Gated Community		A	B	C
AOP	30 m	35.38	30.03	82.58
	40 m	47.18	40.04	110.11
	50 m	58.97	50.05	137.63

The study undertaken by Seago *et al.* (2004) recorded the assessed utilities as comprising pressures in the range of 30 to 75 m with an AOP of 49.1 m. With similar pressure readings, GCs A and B were recorded as having an average UARL of approximately 58.97 L/con/d and 50.05 L/con/d respectively for the AOP of 50 m. The approximated UARL values are

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relatively similar to the average UARL of 59.93 L/con/d presented in Seago *et al.* (2004) research.

The workings presented in Table 2-7 highlight certain correlations between area densities (no/km) and the resultant UARL. A higher populated density revealed relatively lower UARL readings. GC A comprises plot sizes averaging 720 m^2 as opposed to GC B with an average plot area of 360 m^2 and therefore adheres to the preconditioned premise. Furthermore, GC C incorporates significantly larger plot areas in the region of 1 hectare and in so doing, greatly diminishes the density. With the prior supposition taken into account, an average UARL of 137.63 L/con/d for the specified distribution system is justifiable.

6.3 The infrastructure leakage index

The ILI values were determined through the implementation of Equation 2-3 so as to assess the overall management of the water network infrastructure for the specified GCs. The performance indicator is based on the capacity for which a system is able to be managed, maintained, repaired and rehabilitated. Presented in Table 6-8 are the ILI ranges in connection to the control of real losses, associated with the current operating pressures for GCs A, B and C.

Table 6-8: ILI range for GCs A, B and C

		ILI		
Gated Community		A	B	C
AOP	30 m	0.61 - 15.79	0.99 - 11.91	0.68 - 8.83
	40 m	0.46 - 11.84	0.74 - 8.94	0.51 - 6.62
	50 m	0.37 - 9.47	0.60 - 7.15	0.41 - 5.30

The application of the non-dimensional ILI allows for comparisons between different countries of origin for the purpose of leakage control. Lambert *et al.* (1999) reported an ILI range of 0.7 to 10.8 for a dataset comprising 27 diverse distribution systems. The findings presented in Table 6-6 established GC A as having an ILI range of 0.4 to 15.8 for the associated operating pressures. The study conducted by Seago *et al.* (2004) reported comparable ILI values ranging between 0.08 and 15.96. GC B held values as low as 0.6 while reaching a high of 11.9 whereas GC C recorded an ILI range of 0.4 to 8.8.

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A relatively lower range in ILI values were derived for the collective distribution systems as opposed to the workings presented by Lambert *et al.* (1999). As previously suggested in Section 6.2, an adjustment to the UARL component for GCs would additionally result in higher ILI values.

Illustrated in Figure 6-1 is an extract of the approximated ILI values associated to GC B for an AOP of 40 m. Note, Figure 6-1 comprises a number of consecutive daily ILI readings with zero omitted days. The specified distribution system read a steady ILI followed by a gradual upsurge with an abrupt drop. The findings presented suggest the detection and rehabilitation of a potential mains leak within the water network preceding the stabilization of the ILI. Further research could investigate potential trends and in so doing identify the growth of smaller undetected leaks prior sudden pipe bursts.

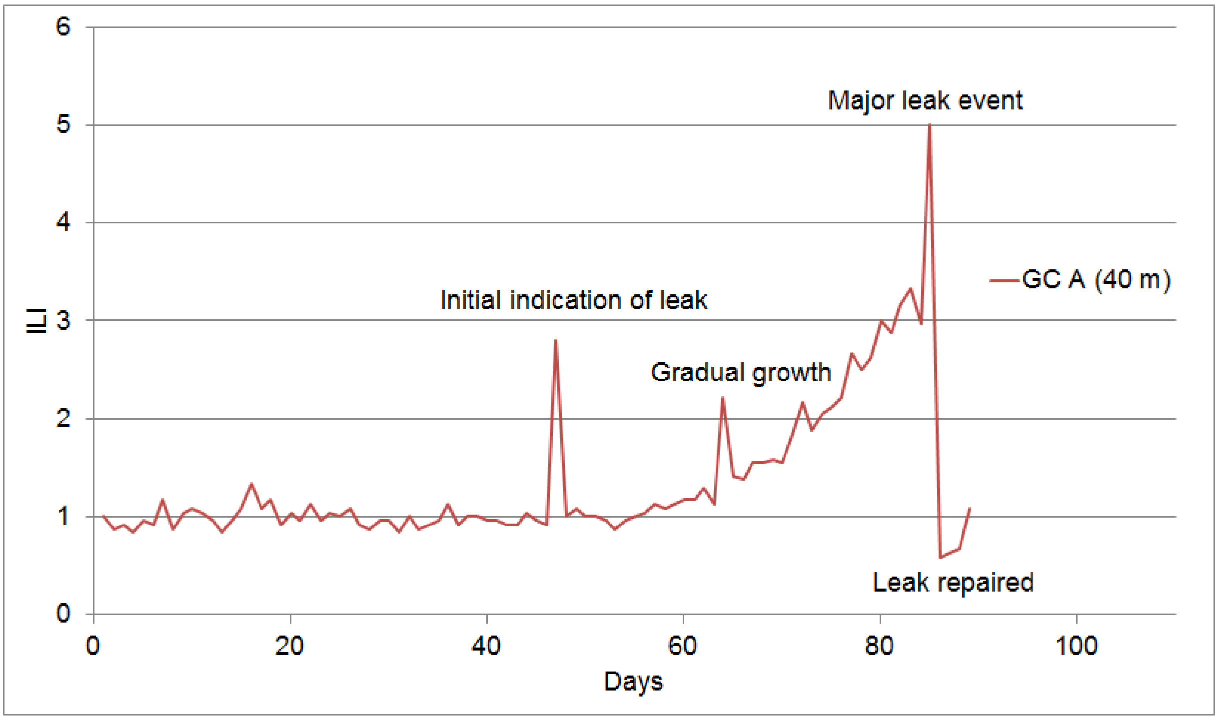

Figure 6-1: ILI plots for GC B

According to Lambert and McKenzie (2002), the greater the amount by which the ILI exceeds 1.0, the higher the need for further management of real losses. The values representative of the average ILI for the selected distribution systems are summarised in Table 6-7 for the chosen AOP range. GC A measured an average ILI of approximately 1.51 for which GCs B and C reported averages of 1.28 and 1.77 respectively. The findings presented in Table 6-8 highlight a reduction in the ILI for higher operating pressures. According to Winani (2009), pressures are a contributing factor in the implementation of the UARL component. In stipulating the AOP associated with the ILI values; views can be taken as to whether an opportunity exists to undertake pressure management. Note, the ILI solely provides an indication of the leak detection and repair performance within the distribution systems.

Lambert *et al.* (1999) reported an average ILI of 4.38 for the associated water networks across 20 countries. Seago *et al.* (2004) assessed the levels of leakage in accordance to 30 water utilities across South Africa with a resultant ILI averaging 5.69. Based off the workings of Seago and McKenzie (2007), Table 2-8 presented in Section 2.3.2 stipulates the typical ILI benchmark values for the anticipated level of infrastructure leakage. The findings presented in both prior case studies denote the overall conditions of the analysed water networks as 'Good'. With GCs A, B and C comprising average ILI values within the range of 1 to 4, Table 2-7 suggests 'Excellent' infrastructure.

Table 6-9: Average ILI for GCs A, B and C

Infrastructure Leakage Index (ILI)				
Gated Community		A	B	C
AOP	30 m	1.92	1.63	2.26
	40 m	1.44	1.22	1.69
	50 m	1.15	0.98	1.36
Average		1.51	1.28	1.77

The findings presented in Table 6-9 are representative of GCs that are responsible for the management and upkeep of the specified water networks. With the aforementioned abnormalities taken into account, a relatively lower ILI is considered likely. However, the ILI values are exceptionally low, for SA conditions. This is possibly due to better water distribution system operation and management in GCs than evident elsewhere. The workings published by Lambert *et al.* (1999) and Seago *et al.* (2004) were conducted on normal distribution systems that were held accountable by municipal authorities. In so doing, the research highlights certain discrepancies during the assessment of real losses for typical water networks compared to systems operated by GCs. Further research could provide the needed adjustments when analysing the extent of real losses within GCs.

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7. Conclusion

The purpose of the chapter is to conclude on the findings presented throughout the research in assessing real losses from drinking water networks operated by GCs. The review of relevant literature sourced from numerous scientific journals and published articles contextualised current information and developed a background in residential water loss. A formulated mathematic model was implemented by means of stringent measures following a step-by-step methodology approach. Results were derived and correlated with the workings of prior published case studies, both domestic and international. Findings were critically evaluated and in so doing, provided contextual commentary on the results. Furthermore, the chapter assesses the usefulness of the research and offers recommendations for future work.

7.1 Summary and key findings

The main aim of this research was to answer the problem statement posed in Section 1.2. The scope of the research was limited to the assessment of distribution systems located in the Western Cape Province. A categorisation process was implemented from which three distribution systems, denoted as GC A, B and C, were selected from a range of 24 potential stands. The categorisation process took account of site locations, length of data records as well as demarcated land zones. Bulk meter flow rates were collected at regular intervals of 15 minutes between 1 October 2018 and 30 September 2019 for the specified GCs.

A stringent selection model was formulated to locate a specific number of consecutive no-flow readings and omit the day from the database should it not satisfy the preconditioned requirement of 1 hour. Suspicious flows falling adjacent to removed days were flagged for further investigation. Consequently, a data record catalogue was consolidated for each specified water network. GC A resulted in 242 usable days comprising 23 232 flow recordings. GCs B and C reported 12 096 and 19 584 flow recordings respectively. The flow recordings analysed in the research are representative of the legitimate consumption of all the individual GC consumers, water leakage and losses in plumbing systems of all consumers, water use by the GC for common purposes, and water leakage and losses in the GC water distribution system.

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A verification process investigated the maximum flow readings and the peak flow calculations based on the CSIR (2019) criteria. Furthermore, correlations were made in accordance to the workings stipulated in the Du Plessis and Jacobs (2018) case study regarding the AADD/plot size. Both comparative measures reported feasible flow recordings with an acceptable data range.

The MNF method was implemented for GCs A, B and C from which the lowest one hour flow rate was sourced from the early morning period, denoted as 2 to 4 am for urban situations (Pearson, 2019). Table 7-1 summates the average night flow and average household night flow per GC, recorded between the hours of 2 and 4 am. Furthermore, presented within Table 7-1 are the average MNF and daily average household MNF, sourced from the night flow register. Note the MNF sourced from the night flow period is relatively higher at night and would not be constant throughout the day.

Table 7-1: Average night flows and MNF

Gated Community	A	B	C	Units
Average Night Flow	0.11	0.14	0.18	L/s
Average Household Night Flow	79.48	74.46	204.49	L/d.con
Average MNF	0.10	0.09	0.17	L/s
Daily average Household MNF *	68.02	48.98	186.55	L/d.con

* Assuming constant MNF throughout the day

Table 7-2 presents the GC-specific input parameters pertinent to the approximation of the components of water leakage and loss within the specified distribution systems. Note, the water pipe network topologies for the three GCs were not available at the time of research. Consequently, certain input parameters, including the components of Lm and Lp were unobtainable. The Lm component was estimated by considering the length of the roads in each GC whilst the Lp comprised the summation of distances measured between the property boundary and individual households. With GCs A and B comprising average plot sizes 720 m^2 and 360 m^2 respectively, the preconditioned premise stipulated in Section 2.3.1 was applied. In so doing, the component of Lp was omitted as individual consumer meters were assumed to be located at the property boundary. However, with a substantially larger average plot size of 8800 m^2, the Lp component for GC C became a contributing factor. The number of connections (Nc) is representative of the number of occupied units during the time of research. Lastly, with a constantly fluctuating AOP, pressures of 30 m, 40 and 50 m were chosen for analyses.

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Table 7-2: System specific input parameters

Gated Community	A	B	C	Units
Average plot size	720	360	8800	m^2
No. of connections (Nc)	122	161	77	con
Length of mains (Lm)	2.57	1.80	4.07	km
Length of private service (Lp)	0.00	0.00	3.08	km
Average operating pressure (AOP)	30 - 50			m

The findings in connection to the GCs' consumption and water loss and leakage, defined within the IWA standard water balance, are presented in Table 7-3 for the selected distribution systems. GCs are relatively smaller than water systems of towns and cities, operated by municipalities. The GC staffs are also held directly accountable by the Home Owners Association, resulting in better management, system operation and maintenance than is possible at the larger municipal scale. The result is better infrastructure management, greater meter accuracy, efficient leak detection and faster repair response times. Consequently, lower water losses are to be expected for these smaller, well maintained and self-managed distribution systems.

Table 7-3: Summation of water loss components

AOP	Gated Community		
	A	B	C
SIV (kL/d)			
NA	40.02	51.29	27.45
CARL (kL/d)			
NA	8.30	7.89	14.36
UARL (kL/d)			
30 m	4.32	4.83	6.36
40 m	5.76	6.45	8.48
50 m	7.19	8.06	10.60
ILI (dimensionless)			
30 m	1.92	1.63	2.26
40 m	1.44	1.22	1.69
50 m	1.15	0.98	1.36

The CARL component held relatively close similarities in accordance with the workings of prior international studies. However, research conducted in South Africa reported slightly

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higher rates of loss and thus, highlighted certain discrepancies between municipal and GC owned water networks. The research reported a moderately lower 21 % and 15 % water loss for GCs A and B respectively. GC C recorded a relatively higher loss of 52 % in relation to the SIV component. Based on GC C housing more agricultural developments as opposed to smaller individual units in GC A and GC B, the impact of night time irrigation on LDNC becomes apparent.

The values representative of the UARL component signify the lowest achievable volume of loss for water networks in good condition and are determined by means of Equation 2-1 for GCs A, B and C. The UARL values presented in Table 7-3 were dependent on the system specific input parameters illustrated in Table 7-2 for a chosen AOP range of 30 to 50 m. The three selected distribution systems reported relatively comparable findings with the workings of prior studies conducted in the late 1990's. However, advancements in leak detection and control management suggest slightly lower values for a more feasible UARL representation, discussed further in the Section 7.2.

The non-dimensional performance indicator, denoted as the ILI component, was implemented so as to assess the overall management of the specified water networks' infrastructure. The ILI provides an indication of leakage detection and repair performance, with lower values suggesting better performance. Theoretically, the ILI value cannot drop below 1.0. The findings suggested that GCs A, B and C comprised 'Excellent' infrastructure with sufficient planning, construction and high operational maintenance activity. The ILI values are exceptionally low for SA conditions.

7.2 Recommendations for Future Work

The process followed in the approximation of the CARL for GCs A, B and C negated the impact associated to the LDNC component. With flow readings extracted from the MNF period, when consumption levels were considered minimal, the LDNC was assumed to be minor and have little/no effect. However, GC C is unique in the fact that it comprises high income homeowners residing on individual one hectare plots. Demarcated as more agricultural land, developments are equipped with large swimming pools and the capacity to accommodate equestrian facilities. Consequently, a component of irrigation and the refilling of swimming pools becomes a plausible factor during nightfall due to evaporation rates and low levels of consumption (Park and Smith, 2008). In practice, methods used to determine the extent of LDNC are somewhat improbable as fluctuations soon become apparent.

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Further research could potentially investigate the LDNC component for GC C so as to implement the means in quantifying its effects. The application of the 3.69 L/prop/h LDNC, as suggested by Fanner *et al.* (2015), sees a reduction in the CARL from 52 % to a more plausible 27 %.

The implementation of the UARL equation was initially established by Lambert *et al.* (1999). Since then, advancements in leakage control and management have meant gradual reductions concerning real losses within water networks. Consequently questioning the validity of Equation 2-1 as resultant values may potentially be out dated. Moreover, this research focused exclusively on water networks operated by GCs as opposed to normal distribution systems held accountable by municipal authorities. Future research could potentially provide suitable adjustments to UARL approximations for these small, well maintained and self-managed systems as they differ from the rest.

Presented in Figure 6-1 is a range of consecutive ILI approximations associated to GC B for an operating pressure of 40 m. Figure 6-1 depicts a steady ILI followed by a gradual upsurge with an abrupt drop. The findings suggest the detection and rehabilitation of a potential mains pipeline leak within the specified distribution system preceding the stabilization of the ILI. Further research could potentially investigate possible trends and in so doing, identify the growth of smaller undetected background leaks prior the escalation of a sudden pipe burst.

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Appendix A

This appendix encompasses the Microsoft Excel spread sheets formulated in answering the problem statement posed in Section 1.2. Due to the extent in flow records, the complete dataset cannot be displayed. However, if needed, records can be made accessible upon request.

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A.1 Unavoidable annual real losses (UARL) parameters

Table A-1: Lambert *et al*. (1999) UARL parameters

Infrastructure Component	Background losses	Reported bursts	Unreported bursts
Mains	20 L/km/h*	0.124 bursts/km/year at 12 m^3/h* for 3 days duration	0.006 bursts/km/year at 6 m^3/h* for 50 days duration
Service connections to edge of street	1.25 L/conn/h*	2.25/1000 conn/year at 1.6 m^3/h* for 8 days duration	0.75/1000 conn/year at 1.6 m^3/h* for 100 days duration
Service connections after edge of street #	0.50 L/conn/h*	1.5/1000 conn/year at 1.6 m^3/h* for 9 days	0.50/1000 conn/year at 1.6 m^3/h* for 101 days

* All flow rates quoted at 50m pressure

For 15m average length

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A.2 Legitimate domestic night consumption (LDNC) Case Study

Table A-2: Complete LDNC values (Fanner et al., 2015)

CMA No.	Site Name	No. of Props	No. of Days	LDNC (L/prop/h)
4045	Tickenham	218	38	5.79
7022	Bishop Sutton	284	42	7.75
1094	Wickwar	188	55	2.77
2131	Little Stoke	275	24	3.13
2131	Little Stoke	275	49	5.15
1133	Frampton	268	40	2.74
1138	Winterbourne	188	41	7.84
8310	Weston	89	35	1.82
8310	Weston	89	33	1.99
8311	Hotwells	132	31	1.55
8311	Hotwells	132	29	2.12
8313	Clutton	114	44	1.37
8316	Downend	96	24	2.14
8316	Downend	96	52	1.71
2246	Henbury	163	32	4.43
2246	Henbury	163	44	3.78
2246	Henbury	163	34	5.31
3172	Chessel	959	46	1.85
2268	Ashley Down	212	62	4.2
2132	Patchway	778	47	3.15
3044	Stockwood	987	35	1.77
3044	Stockwood	987	33	2.41
8319	Hartcliffe	111	35	4.97
8319	Hartcliffe	111	56	4.36
8319	Hartcliffe	111	29	1.52
2275	Eastville	482	27	3.36
2275	Eastville	482	25	4.39
3112	Totterdown	670	25	3.75
3174	Southville	887	33	8.07
2277	St Werburghs	416	47	4.26
3416	Lawrence	616	40	5.02
8324	Kingswood	182	30	2.68
2332	Hillfields	705	32	3.32
3101	Knowle	853	32	4.75
8325	Hortfield	111	40	1.8
8325	Hortfield	111	46	4.62
Total		12004	789	3.69

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A.3 Categorisation process (Phase 1)

Table A-3: Complete summation of phase 1

Stand Number	Western Cape	Adequate Record Length	Gated Community (GC)
1	NO	YES	NO
2	YES	YES	YES
3	YES	YES	NO
4	NO	NO	NO
5	YES	YES	YES
6	YES	YES	NO
7	YES	YES	NO
8	YES	YES	NO
9	NO	NO	NO
10	YES	YES	YES
11	YES	NO	NO
12	YES	YES	NO
13	YES	YES	NO
14	YES	NO	NO
15	NO	NO	NO
16	YES	YES	NO
17	YES	NO	NO
18	YES	NO	NO
19	YES	NO	NO
20	YES	YES	NO
21	YES	YES	NO
22	YES	YES	NO
23	YES	YES	NO
24	YES	YES	NO
TOTAL	20	16	3

A.4 Selection Model

A						GAPS ALLOWED :			TEST
DATE			TIME	FLOW		4	X15 min		INCLUDE = 1 EXCLUDE = 0
Year	Month	Day	hr:min:sec	L/s		CONSECUTIVE MISSING DATA			
2018	10	1	00:00:00	0.09		0			1
2018	10	1	00:15:00	0.07		0			1
2018	10	1	00:30:00	0.06		0			1
2018	10	1	00:45:00	0.06		0	0		1
2018	10	1	01:00:00	0.08		0			1
2018	10	1	01:15:00	0.07		0			1
2018	10	1	01:30:00	0.06		0			1
2018	10	1	01:45:00	0.06		0			1
2018	10	1	02:00:00	0.06					1
2018	10	1	02:15:00	0.06					1
2018	10	1	02:30:00	0.04					1
2018	10	1	02:45:00	0.07					1
2018	10	1	03:00:00	0.06					1
2018	10	1	03:15:00	0.06					1
2018	10	1	03:30:00	0.06					1
2018	10	1	03:45:00	0.07					1
2018	10	1	04:00:00	0.08					1
2018	10	1	04:15:00	0.10		1			1
2018	10	1	04:30:00	0.09		1			1

Figure A-1: Selection Model extract

A.5 Average Plot Size

Table A-4: Average plot sizes

Plot area sizes (m^2)			
Plot	A	B	C
1	710	210	8459
2	700	290	8477
3	700	348	8256
4	751	340	8310
5	715	516	8510
6	704	561	8572
7	713	242	9640
8	786	376	9433
9	700	224	8281
10	700	212	9063
11	710	558	8531
12	700	378	10048
Average =	716	355	8798

A.6 Actual Average annual daily demand (AADD)

A								SUMMARY	
DATE			TIME	FLOW	FLOW	FLOW		FLOW	FLOW
Year	Month	Day	hr:min:sec	L/s (15 min)	L/s (1 hr)	L/s (day)		L/s (1 hr)	L/s (day)
2018	10	1	00:00:00	0.09				0.07	0.33
2018	10	1	00:15:00	0.07				0.06	0.33
2018	10	1	00:30:00	0.06				0.06	0.45
2018	10	1	00:45:00	0.06	0.07			0.06	0.34
2018	10	1	01:00:00	0.08				0.09	0.36
2018	10	1	01:15:00	0.07				0.14	0.22
2018	10	1	01:30:00	0.06				0.26	0.24
2018	10	1	01:45:00	0.06	0.06			0.58	0.38
2018	10	1	02:00:00	0.06				0.75	0.36
2018	10	1	02:15:00	0.06				0.70	0.28
2018	10	1	02:30:00	0.04				0.51	0.17
2018	10	1	02:45:00	0.07	0.06			0.46	0.23
2018	10	1	03:00:00	0.06				0.44	0.31
2018	10	1	03:15:00	0.06				0.31	0.46
2018	10	1	03:30:00	0.06				0.34	0.21
2018	10	1	03:45:00	0.07	0.06			0.52	0.27
2018	10	1	04:00:00	0.08				0.82	0.50
2018	10	1	04:15:00	0.10				0.24	0.53
2018	10	1	04:30:00	0.09				0.35	0.54
2018	10	1	04:45:00	0.11	0.09			0.33	0.48

AADD =	0.46	L/s
Max 15 min =	4.06	L/s
Max 1 hour =	2.65	L/s
Max 1 Day =	0.89	L/s
AADD =	0.32	kL/Plot/d

Figure A-2: AADD Calculation extract

A.7 Ranked ILI ratios for different AOP

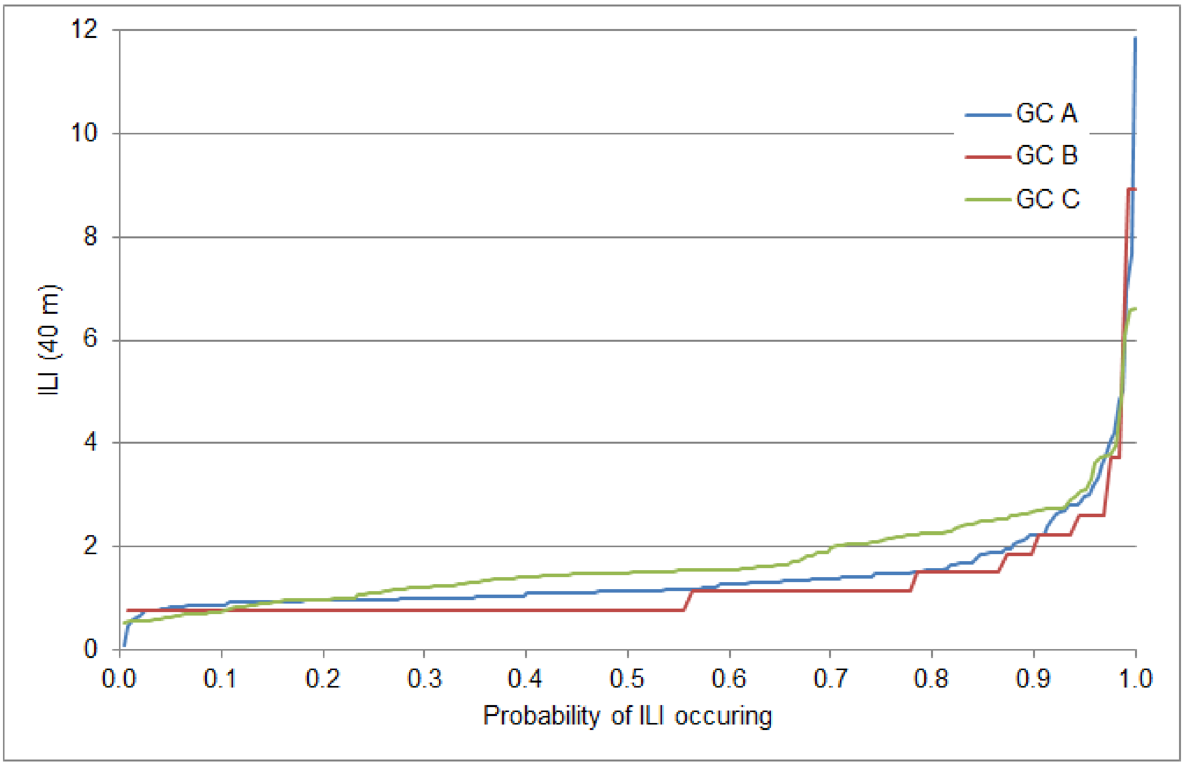

Figure A-3: Non-exceedance probability of ILI for an AOP of 40 m

Stellenbosch University https://scholar.sun.ac.za

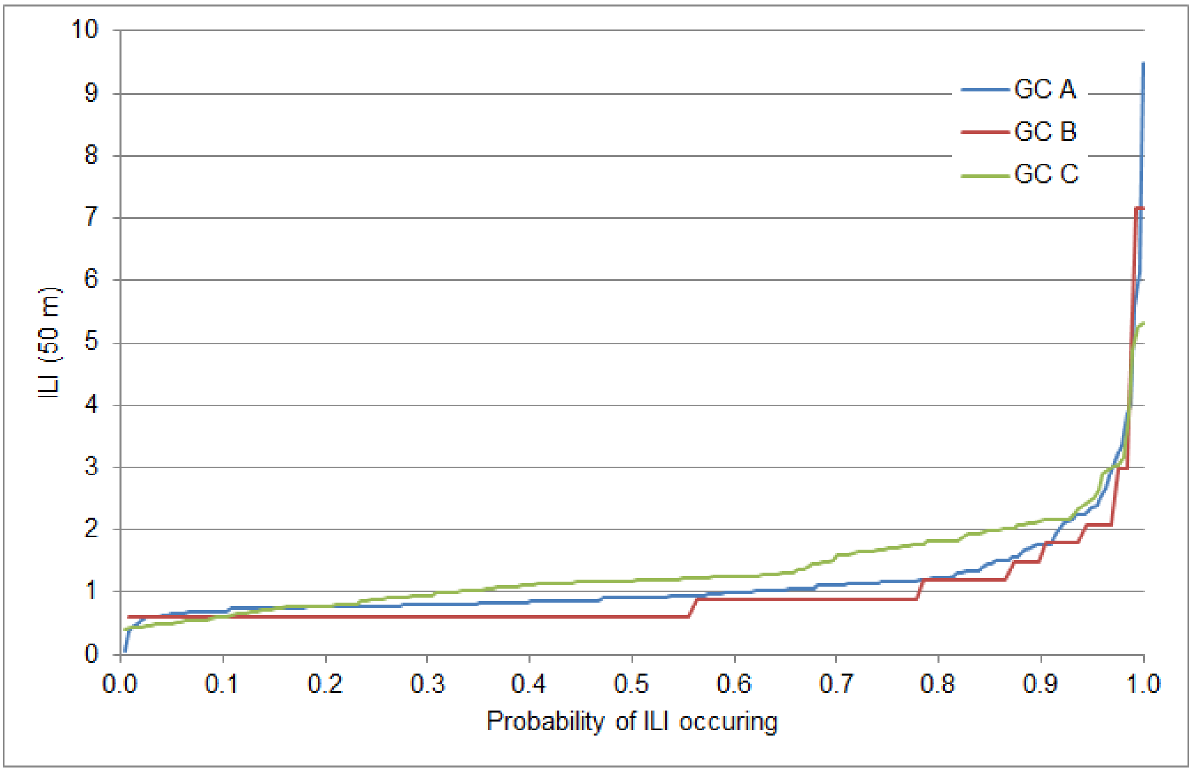

Figure A-4: Non-exceedance probability of ILI for an AOP of 50 m

A.8 Comparative ILI ratios

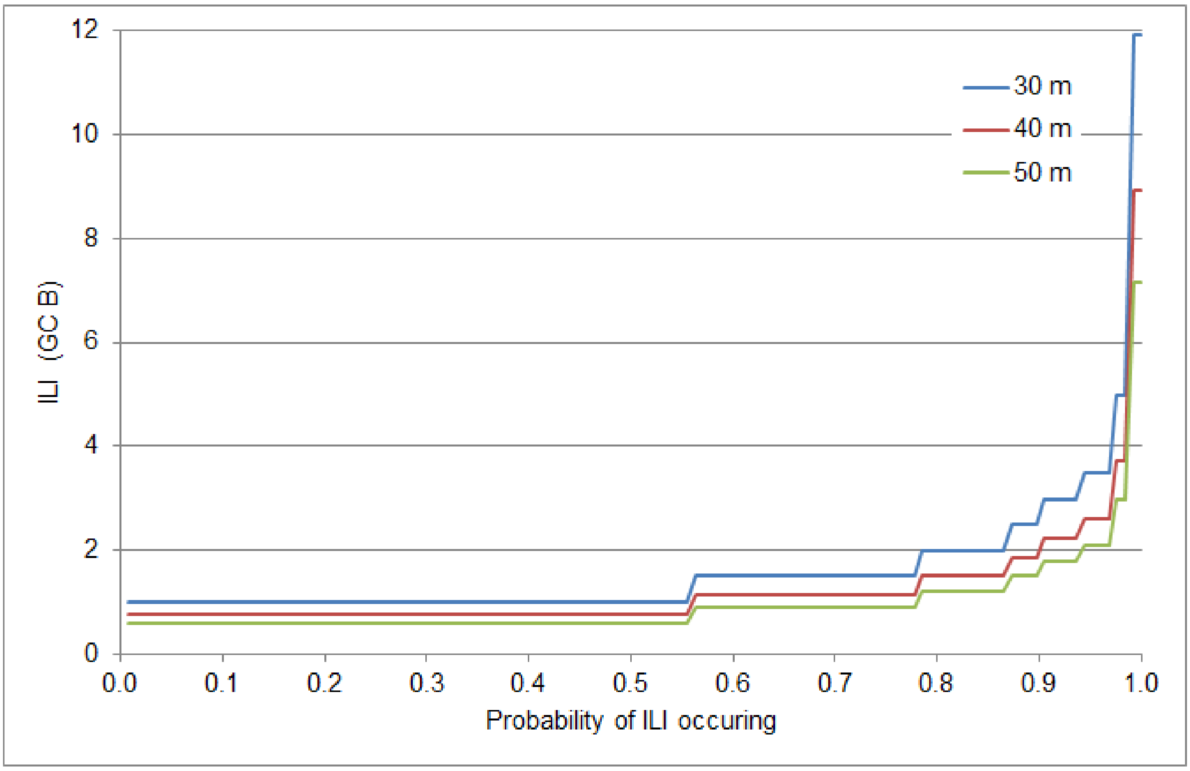

Figure A-5: Non-exceedance probability curve for ILI for GC B

Stellenbosch University https://scholar.sun.ac.za

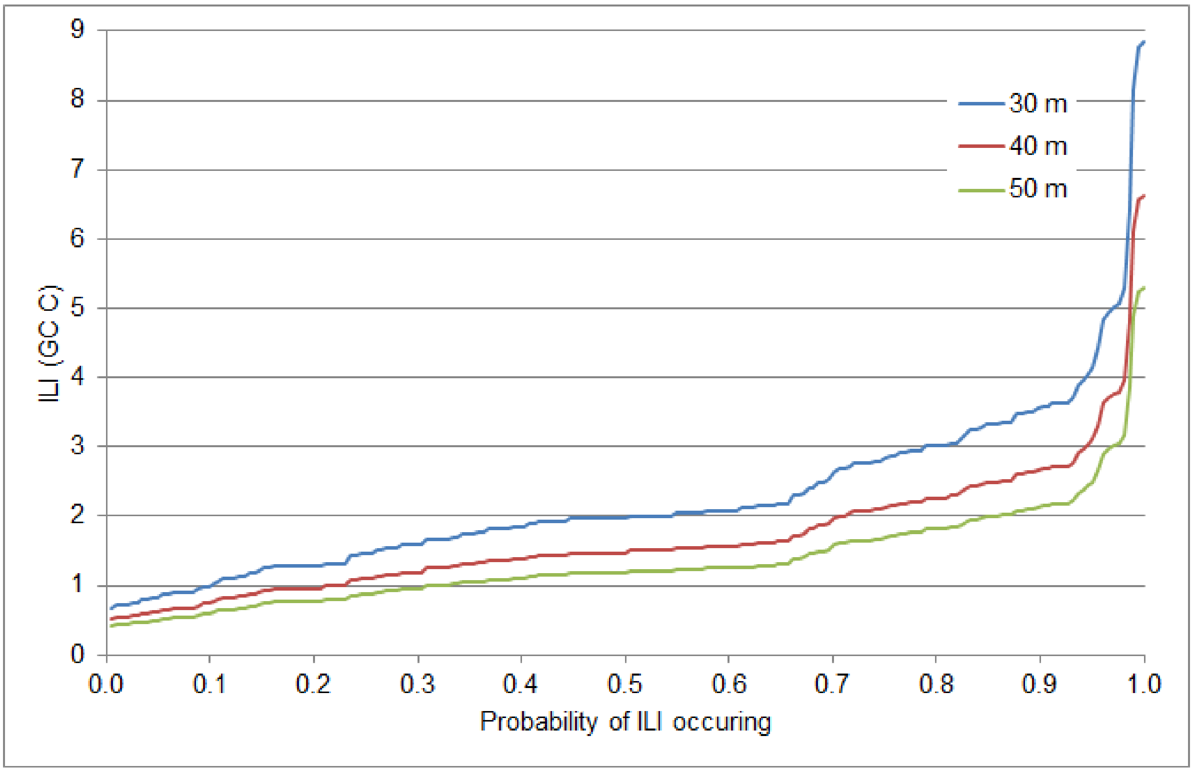

Figure A-6: Non-exceedance probability curve for ILI for GC C